

TERC

PHYSICS OF TECHNOLOGY

COORDINATED BY AMERICAN INSTITUTE OF PHYSICS



THE PRESSURE COOKER

Thermal Properties of Matter.

THE PRESSURE COOKER

A Module on the Thermal Properties of Matter

TERC

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The Pressure Cooker

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PREFACE

ABOUT THIS MODULE

Its Purpose

The purpose of the *Physics of Technology* program is to give you an insight into some of the physical principles that are the basis of technology. To do this you are asked to study various technological devices. These devices have been chosen because their operation depends on some important physics principles. In this module the device is the pressure cooker. Its design and use depend on the thermal properties of water.

The PoT program has adopted a modular format with each module focusing on a single device. Thus you can select those modules that relate to your own interests or areas of speciality. This preface highlights some of the features of the modular approach so that you may use it efficiently and effectively.

Its Design

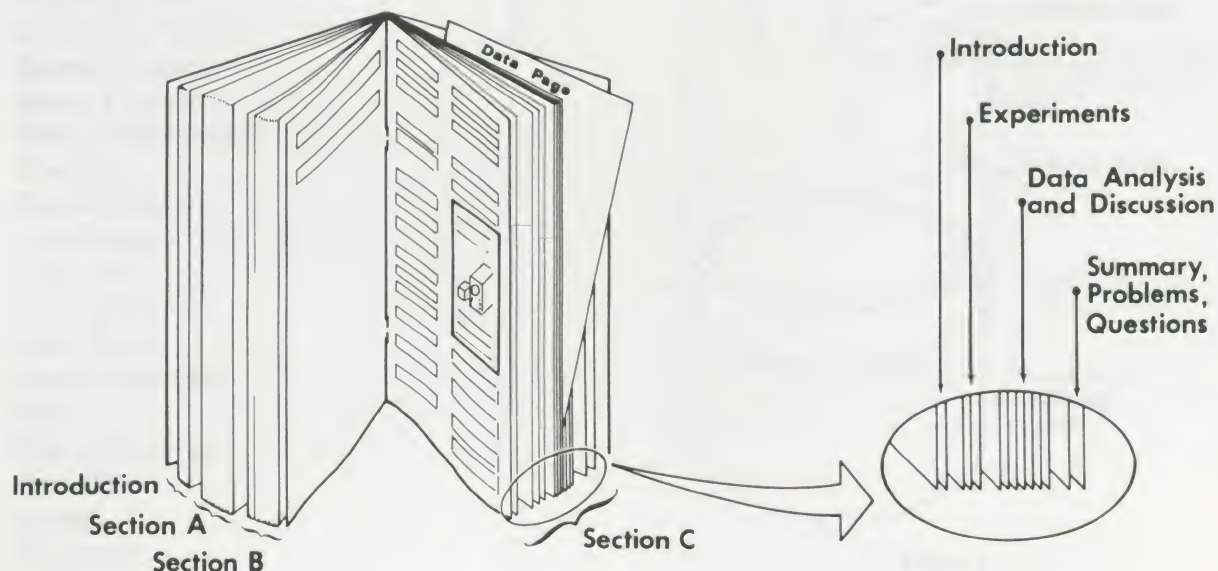
The module design is illustrated below. The *Introduction* explains why we have selected the pressure cooker to study and what physical principles will be illustrated in its behavior. Learning *Goals* are given, as well as

Prerequisite skills and knowledge you should have before beginning. The three *Sections* of the module treat different aspects of the device. They are of increasing difficulty but each can be completed in about one week.

Each section begins with a brief *Introduction* to the topics treated and how they relate to the behavior of the device. The *Experiments* follow and take about two to three hours. Tear out *Data Pages* are provided to record your data. The body of the section then describes the method of *Data Analysis* including a *Discussion* of the physical principles which explain your results. A *Summary* ends the section with *Problems* and *Questions* you can do to test your understanding.

HOW TO USE THIS MODULE

This module has been written so that it can be quickly and easily scanned. That is, you can get the gist of the ideas and experiments by simply flipping from page to page, reading only the headings and italicized words, and looking at the illustrations. Before you begin a section or an experiment, scan through it in this way so that you will know where you are going.



The Experimental Activities

The heart of the Physics of Technology modules is the experimental study of various devices. Such study often involves learning to use a new measuring device or instrument. Since your observations and data usually will be analyzed *after* you leave the laboratory, it is important that you do the experiments carefully and that you take accurate data. A scan of the Data Analysis and Discussion *before* you begin the experiment will help you to know what aspects of the experiment and data are important.

The Data Analysis

The data you take will often have to be graphed to make it easier to understand. Graphing and graphical analysis are essential parts of experimental science. Understanding

graphs is important for technology since technical information is often presented graphically. For these reasons, and since the discussion of your results will be based on your graphs, it is important that you prepare them clearly and accurately.

Review

When you finish a section you should again scan it to be sure you understand how the ideas were developed. Reading the *Summary* will also help. Then you should try to answer the *Problems* and *Questions* to test your understanding and to be sure that you have achieved the *Goals* for that section. When you have completed the module, you may want to tear out certain pages for future reference; for example, conversion tables and methods of calibrating instruments.



THE PRESSURE COOKER

INTRODUCTION

ABOUT THE PRESSURE COOKER

Why Is It Used?

The common pressure cooker is found in many kitchens. It is a time-saving appliance because it shortens the cooking time for many foods. As you probably know, water normally boils at 212°F. But in a pressure cooker the boiling temperature can be raised to 255°F. This is a small difference, but it is important for many processes such as cooking. Cooking results from chemical reactions which occur in the food. At temperatures near the boiling temperature of water, the rate of these reactions doubles for every 18°F increase in temperature. Thus a small increase in temperature can mean a substantial shortening of cooking time.

How Does It Work?

Another advantage of the pressure cooker for cooking is that, in addition to raising the boiling temperature, the higher temperature can be kept constant. By controlling the *pressure* in the cooker (which is fairly easy to do) you can control the *temperature* of the boiling water.

In the home pressure cooker, the pressure is about 15 pounds per square inch. While that may not sound like very much pressure, it results in a force on the lid of hundreds of pounds. This pressure is controlled with just a three-ounce weight. See Figure 1.

Table I.
Typical Cooking Times

FROZEN VEGETABLES	Cooking Time In Minutes
Asparagus, Cut	2
Asparagus, Spears	2
Beans, Cut Green	1
Beans, Cut Wax	1
Beans, French Style	1
Broccoli	2
Brussel Sprouts	2
Cauliflower	1
Corn, Cut	1
Corn on Cob	2
Lima Beans	2
Mixed Vegetables	2
Peas	1
Peas and Carrots	1
Spinach	1
Squash	7
Succotash	2

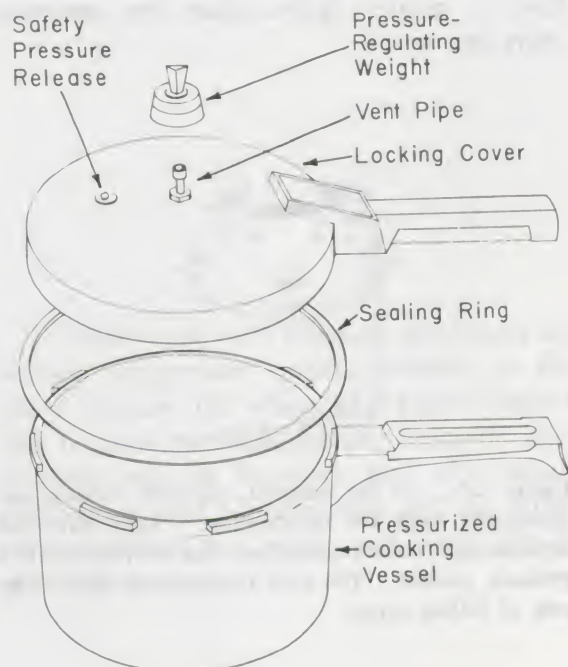


Figure 1.

WHY STUDY THE PRESSURE COOKER?

It Uses Important Physical Principles

The pressure cooker is not a typical device for study in a physics course. But the operation of this simple household appliance involves a number of important physical ideas. For example, its operation involves two basic physical quantities, *temperature* and *pressure*, which are continually encountered in modern technology. But what are these quantities? How are they measured and controlled? What dangers are involved? This module will help to answer these questions.

Also, the pressure cooker uses water. The water gets hot, boils to become steam and the steam disappears into the air, often reappearing as water droplets on cool surfaces. This raises some important questions about matter. What forms can it take? How much energy is involved when matter changes form? What are the effects of temperature and pressure?

These are just some of the questions you will explore in studying the pressure cooker. When you have finished this module you should have gained a good understanding of the simple pressure cooker. You may also have a greater appreciation for common, every-day water.

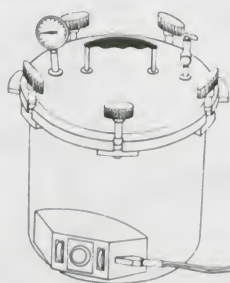


Figure 2A. In the hospital, pressure cookers are commonly used for sterilization. They have the sophisticated name of *autoclave*, but are identical to a pressure cooker. The high temperature speeds the rate of killing germs.

There Are Many Applications

The physical principles that underlie the operation of the pressure cooker are used in many other devices. (Figure 2A, B, and C.)

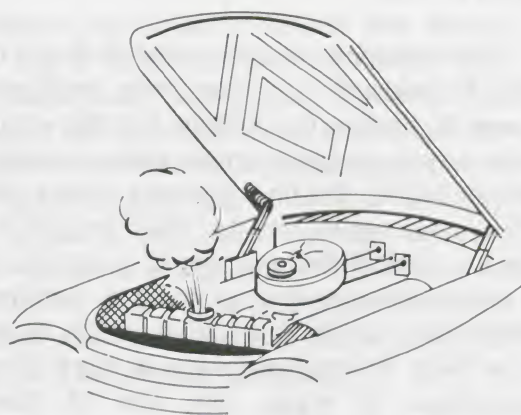


Figure 2B. Modern automobile cooling systems are a coolant under pressure. This raises the temperature of the coolant to almost 260°F without boiling. The higher temperature increases the cooling efficiency.

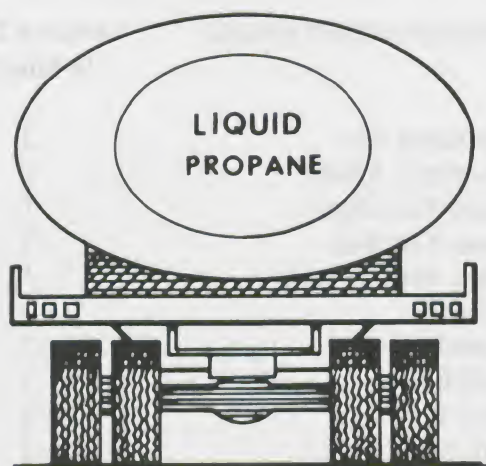


Figure 2C. Propane, which is used in cooling and heating, is a *gas* at normal temperature and pressure. At high pressure, however, it changes to a liquid. As a liquid it is much easier to store and transport.

WHAT WILL YOU LEARN?

SECTION A: Energy and Phases of Matter

Before you study the behavior of the pressure cooker you will study the substance on which its operation depends, namely water. When water boils, it changes from a liquid to a vapor (steam). *Liquid* and *vapor* are two of the three basic *phases*, or forms, in which matter can exist. The other phase is the *solid phase*. The solid phase of water is, of course, ice.

In Experiment A-1 you will heat some ice until it changes to water and boils to

become steam. In the process you will carefully measure the change in temperature with a thermometer called a *thermistor*. The thermistor will be used in later experiments to measure the temperature inside the pressure cooker when the lid is closed.

From your data you will be able to determine the amount of *energy* required to heat water and cause *phase changes*. This energy has important implications for physics and technology.

SECTION B: The Gas Phase and the General Gas Law

Section B is concerned with the gas phase. This phase of matter is the easiest to describe mathematically, since a single equation, called the *General Gas Law*, can describe the behavior of any gas under certain conditions.

In Experiment B-1 you will heat up the pressure cooker, remove it from the heat and close the lid. Then you will measure the

pressure and temperature inside as it cools and the pressure decreases. From your data you will be able to determine the *absolute zero* of temperature and see the basis for the *Kelvin* scale of temperature.

You will also learn to calculate the force on a surface under pressure and other useful quantities.

SECTION C: Phase Diagrams

In the final experiment you will operate the pressure cooker in the way it is used for cooking. As water boils you will measure its boiling temperature and see how it increases with pressure.

Using what you learned in Section B, you can calculate the pressure at which the regulating weight will lift to control the pressure.

Finally you will compare your data on boiling temperature versus pressure to the *phase diagram* for water. This phase diagram will be used to explain many common phenomena such as *humidity* and *dew point*, *evaporation* and *condensation* and the *triple point* at which ice, water, and steam can all exist together.

GOALS

The general goals of this module are to give you an understanding of the physical principles underlying the operation of the pressure cooker.

When you have completed the module, you should know the following:

The manner in which matter is classified into phases.

The energy needed to produce a temperature change for each phase.

The energies needed to produce phase changes.

A way of describing mathematically the vapor phase.

A graphical way of describing the physical conditions under which the various phases will occur.

The effect of pressure on the temperature at which phase changes will occur.

How to measure temperature using a thermistor.

The various units for energy and pressure and how to convert easily from one set to another.

PREREQUISITES

Before beginning this module, you should have the following skills since they will be used but not described in this module.

1. The ability to read meter scales.
2. The ability to determine the mass of an object using a common balance scale.

If you are unsure whether you meet these prerequisites, ask your instructor to give you a prerequisites test.

If you find you do not meet a certain prerequisite, ask your instructor to give you material to help you learn the needed skill.

SECTION A

Energy and Phases of Matter

To begin study of the pressure cooker, a bit of background about matter is needed. For example, how is matter classified? What terms are used to describe its forms? What is the role of energy; of changes in energy? In this part of the module some of these questions will be explained with a simple experiment using water. You will see that the amount of energy required to change its form is large. And you will see that this energy can be used by a wide variety of common devices. Also, you will learn a convenient way of measuring temperature by measuring the electrical resistance of a device called a thermistor.

PHASES OF MATTER

Long ago man recognized that matter occurs only in a small number of different forms, each with its own distinct properties. The Greeks called these forms *earth* (\oplus), *water* (\ominus), *air* (\circ), and *fire* (\odot). *Earths* were substances which were solid and had a definite shape. *Waters* flowed and would fill containers. *Airs* would completely fill a space, yet could easily be compressed to change their sizes. *Fires* were hot and could convert materials from one form to another.

Since then, however, three of the substances, earth, water and air, have been recognized as commonly occurring examples of a broader classification of matter. These broader classifications are called the *states* or *phases of matter*: the *solid* phase, the *liquid* phase and the *gas* or *vapor* phase. But the Greeks weren't far wrong; earth is a solid, water is a liquid, and air is a gas. The properties the Greeks defined for the three phases are largely those we use today.



Figure 3. Top row, the symbols for earth and air. Bottom row, fire and water.

ENERGY AND PHASE CHANGES

The difference between our thinking and that of the ancient Greeks involves the idea that when a material changes its phase, for example water changing to ice, its molecules do not change to become "earth" molecules. They only change their arrangement to that of a solid.

This is where the Greek's "fire" comes in. Fire is a source of *energy*; energy causes materials to change phase. By adding energy we can cause a material to change from a solid to a liquid (*melting*), or from a liquid to a vapor (*vaporization*). (Figure 4.)

By removing energy we can reverse the phase changes. These are *condensation* and *freezing*.



Figure 4. Water freezes at 0°C to become ice; ice melts at 0°C to become water; water boils at 100°C to become vapor (steam); water vapor condenses at 100°C to become water.

THE PHASES OF WATER

Perhaps you've never thought about it, but water is about the only substance that occurs on earth in any significant quantity as a liquid. (Can you think of another?) Not only that, but it occurs in nature in all three of its phases. Can you think of another substance that does that?

The temperatures at which water changes phase are also well known. It boils at 100°C (212°F), changing from a liquid to a vapor in the process. It freezes at 0°C (32°F) to become a solid. The phases of water are so common to us that we have special names for them. The vapor phase is called steam and the solid phase is called ice. (Figure 5.) For no other substance is this done. The reason is that another material in more than one of its phases is seldom encountered.



Figure 5. Ice, water, and water vapor in the air are naturally occurring examples of the solid, liquid, and vapor phases of water. Which phase do you think the clouds represent?

THE PHASES OF OTHER SUBSTANCES

The Usual Case

Since they are rarely seen, do other substances occur in all three different phases? In general, yes, many substances can occur as a liquid, vapor and solid. But it often takes special conditions. Solid iron, for example, is quite common, but liquid iron or gaseous iron is rarely found. These phases can occur, but only at high temperatures. Iron becomes a liquid at 987°C (1808°F) and vaporizes at 1801°C (3273°F). (Figure 6.)

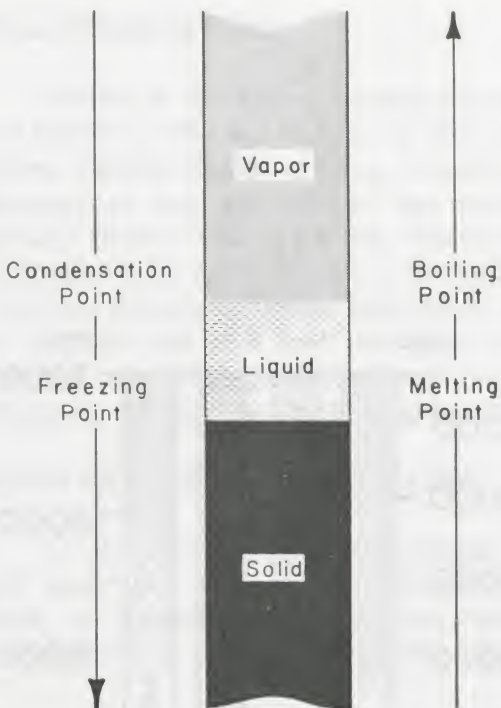


Figure 6.

Oxygen is a common *gas*, and is an essential part of the air we breathe. However, oxygen becomes a liquid when the temperature falls to -361°F , and becomes a solid at -424°F . Mercury is a liquid at room temperature, but it becomes a gas at 332°C (630°F). Most of these temperatures are far beyond those that occur naturally on earth.

Exceptions

Usually, as its temperature increases, a solid changes first to a liquid, then to a gas. But there are some interesting exceptions. Carbon dioxide, for example, changes directly from a solid to a gas at atmospheric pressure. You have probably seen dry ice (this is solid carbon dioxide). It changes directly to a vapor without first becoming a liquid. Such behavior is called *sublimation*.

Another exception is a substance which does not have a definite melting or boiling temperature. A familiar example is glass. When glass is heated it does not change from a

solid to a liquid at a definite temperature. (Figure 7.) Rather, it becomes softer and softer until finally it flows freely.

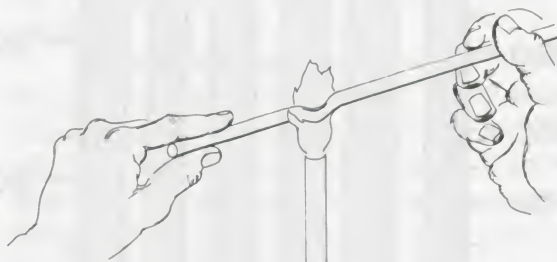


Figure 7.

The range of temperatures for the phases of several common materials are given in Figure 8.

THE IMPORTANCE OF ATMOSPHERIC PRESSURE

Look at the range of temperatures on page 8 for the phases of various materials. First note that the left-hand scale is expanded compared to the right-hand scale. The dotted lines indicate the highest and lowest temperatures ever recorded on earth.* They are the limits of the naturally occurring phases of the various materials.

There is one extremely important qualification we must give to the boiling and freezing temperatures on page 8. That is that *these temperatures only apply when the liquid is at atmospheric pressure*. When the pressure on the liquid changes, these temperatures change. That is the principle behind the functioning of the pressure cooker. These changes for water will be studied in detail in Section C.

*Highest recorded temperature: 134°F , Death Valley, 1913; lowest recorded temperature: -127°F , Antarctica, 1960.

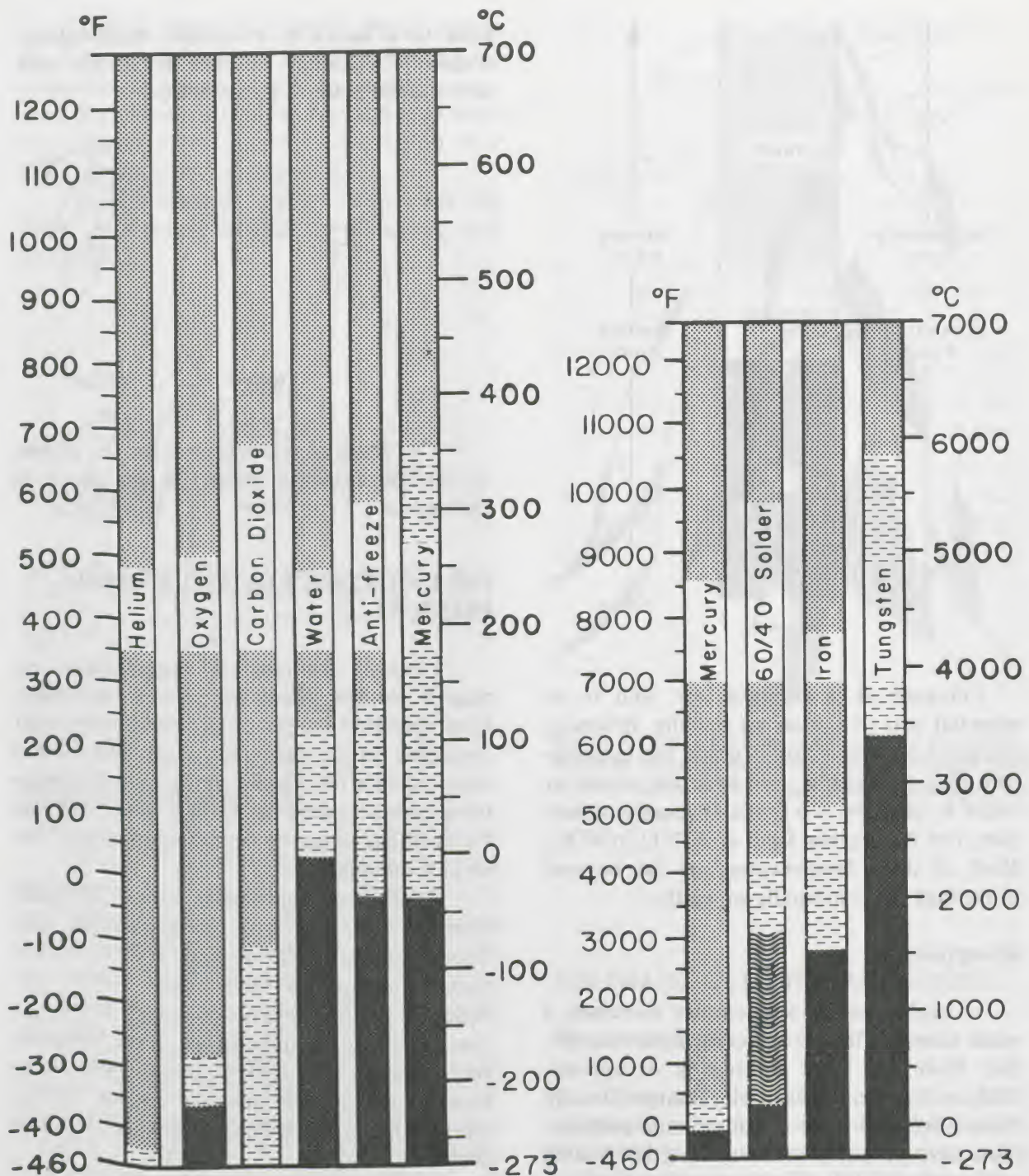


Figure 8. The ranges of temperature for the solid, liquid, and vapor phases of a number of different substances are given here. (The bottom of the scale, $-273^{\circ}\text{C} = -460^{\circ}\text{F}$, is the "absolute zero" of temperature. This concept is discussed in Section B of the module.)

Some Interesting Points

Helium is the only substance that does not become a solid at a pressure of one atmosphere. Carbon dioxide is never a liquid at a pressure of one atmosphere, but *sublimes* directly from a solid to a vapor. The data for antifreeze is for a 50/50 mixture of antifreeze (ethylene glycol) and water. Solder is an alloy of 40% tin and 60% lead that has a single freezing point, but the tin and lead vaporize separately at their own boiling temperatures.

YOUR EXPERIMENTS WITH WATER

In the first section of the module you will study this common and essential ingredient of nature, water. This may seem a diversion from the study of the pressure

cooker, but in fact it isn't. The pressure cooker is specifically designed to make use of certain properties of water. Thus, a study of the pressure cooker must involve a study of water.

In your first experiment you will look at the role of energy. It is energy which causes phase changes. Water is a substance in which all three phases can be studied easily. You will find that the properties of water are used to define two systems of energy units, and that the energy stored in water is used in many important technological ways.

In the first experiment you will also learn to use a *solid-state* thermometer called a *thermistor*. This device will be used later to measure the temperature inside the pressure cooker when the lid is closed.

EXPERIMENT A-1. Using a Thermistor

To measure the temperature you will use a thermistor. It will be discussed in more detail, but for the moment simply think of it as a device whose electrical resistance decreases as the temperature increases.

To determine the resistances which correspond to different temperatures, the thermistor must be *calibrated*. The purposes of this experiment are first to learn how to measure the resistance of the thermistor, then to determine a way of calibrating it.

The electronic symbol for ohms is the capital Greek letter *omega* (Ω). It will be used throughout the module.

Preparation

Examine your thermistor. It should look similar to the one in the illustration. The thermistor is the solid dark disk to which two leads have been soldered. This solder melts at about 180°C . So if you want it to stay together *at no time should the thermistor temperature exceed 180°C .*

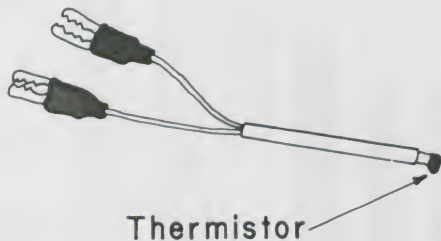


Figure 9.

Examine your ohmmeter. This is an electronic test instrument for measuring electrical resistance in ohms. It is usually part of a more versatile instrument called a *multimeter*, which will measure electric current and voltage as well as resistance portion. A description of the ohmmeter of a multimeter is given on page 11. Take a moment to read and study this description now.

Measuring Resistance

1. Turn the multimeter RANGE SWITCH to the $\times 100$ scale of the OHMS group.

2. Connect the leads together and adjust the Ω ADJUST knob till the meter reads zero.

3. Change the RANGE SWITCH. Does the zero reading change? If it does you must be careful to re-zero every time you change range.

Return to the $\times 100$ range.

4. Disconnect the leads from each other. The pointer should be *exactly* on the far left marker. If it is not, see your instructor for a further adjustment.

5. Connect the thermistor. Use the multimeter to determine its resistance at room temperature. Record your value on the data page at the end of this experiment.

6. On the data page, record room temperature in $^{\circ}\text{C}$ as read from a glass thermometer.

ABOUT THE OHMMETER

The Scale

The scale which is used to measure resistance is usually marked " Ω ." It increases from right to left and there are not equal spaces between the numbers. A battery inside the case provides a voltage V to the resistor to be measured, R . The meter registers the current I that flows. By Ohm's law:

$$R = \frac{V}{I}$$

Calibrating the Thermistor

There are several ways to calibrate a thermistor. We will describe a quick (but not too accurate) way using the manufacturer's data. Later a somewhat more accurate method will be described.

Since the characteristics of a given thermistor may change with time and other factors, it must generally be recalibrated at regular intervals. The calibration should be checked, whenever a thermistor is used. Usually this only requires measuring a single temperature-resistance point, and then adjusting the scale. The procedure below describes how to do this for your thermistor.

On the bottom of the data page you will find two scales. The lower one is marked Resistance (Ω) and the upper one is marked Temperature ($^{\circ}\text{C}$).

1. *Cut the resistance scale out of the data page along the dotted line.*

2. *Line up the two scales as indicated below so that your reading of thermistor resistance coincides with room temperature.*

3. *Tape the resistance scale firmly in this position. From this scale you can now read the temperature that corresponds to each thermistor resistance.*

NOTE: *Neither of these scales have equal spaces between the marks so be careful when you read them. Note particularly that the temperature scale increases from right to left.*

Checking the Calibration

In order to be sure that this calibration scale is accurate you should compare it to a glass thermometer at a couple of temperatures.

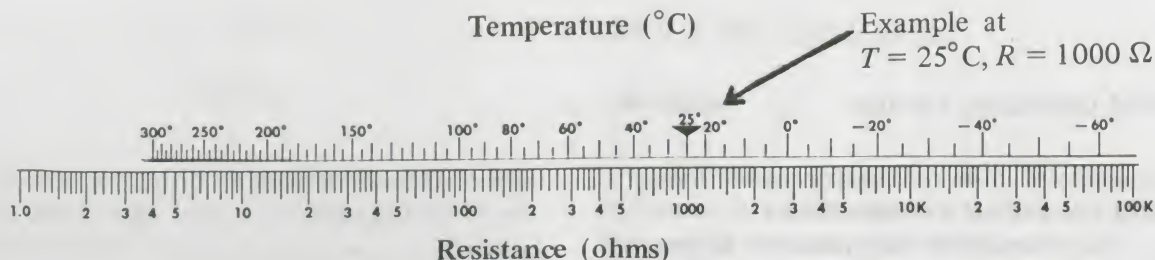
1. *Fill a cup with very hot tap water and immerse the thermistor and the glass thermometer.*

2. *Record the thermistor resistance and thermometer temperature.*

3. *Compare the actual temperature with that on your thermistor scale. Do they agree?*

4. *Repeat for several water temperatures down to ice water.*

5. *Place the thermistor under your tongue to measure your body temperature. Normal human body temperature is about 37°C (98.6°F). Thermistors like this are the sensing element of electronic thermometers used in hospitals.*



EXPERIMENT A-2. Measuring the Energies of Heating and Phase Changes

In this experiment you will measure how much energy it takes to convert a quantity of ice into steam. The ice must go through two phase changes, solid to liquid and liquid to vapor. In addition, the liquid must be heated from the melting point to the boiling point.

To measure the energy required to produce these phase changes you will insulate the ice from outside heat by putting it in a thermos bottle. Then you will supply energy to the ice at a constant rate and record its temperature (measured with the thermistor) as it changes with time. From these data you will be able to calculate the energies of heating and phase changes.

The basic setup for this experiment is shown in Figure 11. The heating energy is

supplied electrically by an ordinary immersion heater used for heating water. To adjust the rate of energy input (or "power") the immersion heater is connected to a Variable Voltage Source. The input power in watts can be calculated from:

$$P = \frac{V^2}{R}$$

where V is the voltage supplied in volts by the variable supply, and R is the resistance of the immersion heater in ohms. You can measure R with the ohmmeter.

One *watt* of power means an input of one joule of energy per second. You will learn more about these units later in this section.

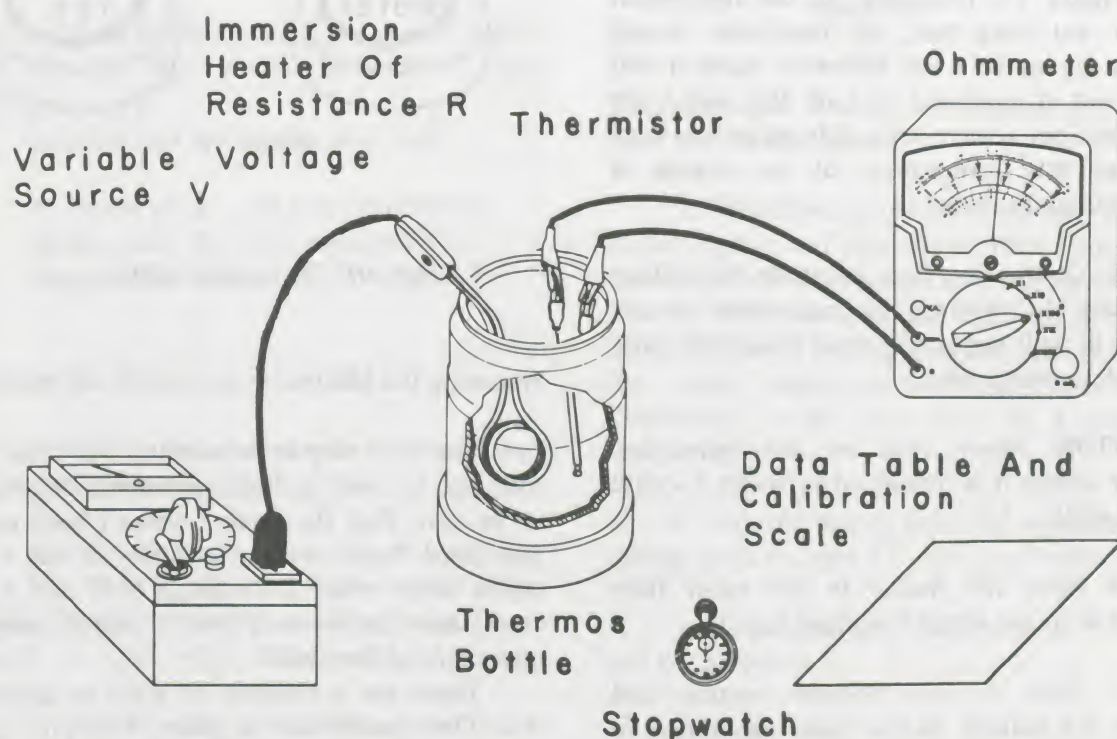


Figure 11.

Determining the Power

In order to determine the power input you need to know the resistance of the immersion heater.

1. *Measure the resistance of the immersion heater* with the ohmmeter and record your value.

This is the resistance at room temperature. Will it change when the heater gets hot? It would be difficult to measure the resistance of the heater when it is plugged into the voltage supply, but you can check it *unplugged* over a range of temperatures. If the temperature does not change significantly then you may assume that it is about the same when it is operating.

2. *Measure the resistance of the immersion heater at the temperature of ice and at the temperature of very hot tap water.* Record your values. Did it change very much? See Figure 12. (Actually, if the immersion heater got very hot, its resistance would change by quite a bit. However, since it will burn out if operated out of the water, its surroundings always keep it from getting very hot, so this assumption of no change is approximately correct.)

3. *On the data page calculate the voltage necessary to produce an immersion heater power of 160 watts.* Use your measured value of heater resistance.

CAUTION: *Never* turn on the immersion heater unless it is immersed in water because it will melt.

4. *Place the heater in the water then plug it in to the variable voltage supply.*

5. *Turn on the variable supply* and adjust the voltage to the value calculated in step 3.

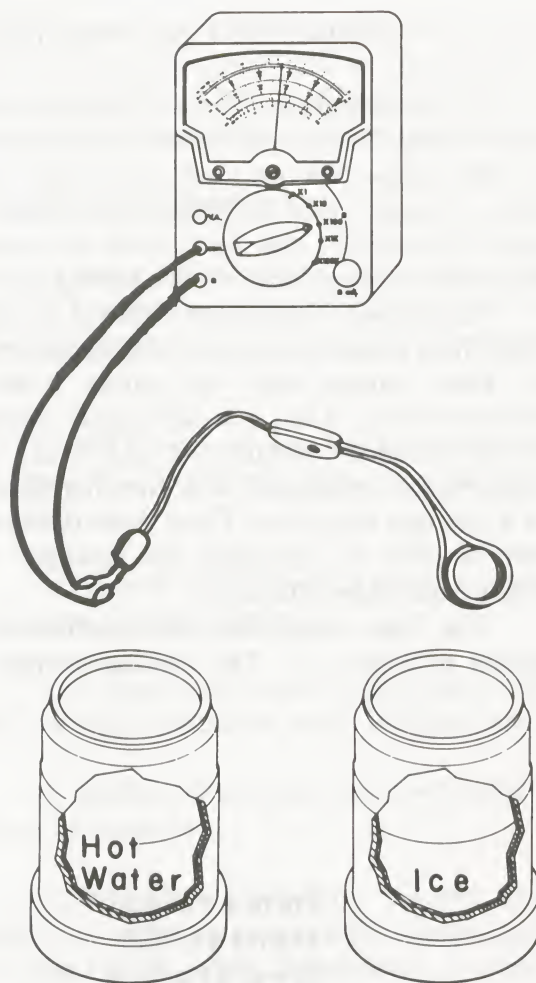


Figure 12.

6. *Turn off the voltage supply.*

Preparing the Mixture

The next step is to measure the mass of water to be used in the experiment. In order to be sure that the heater doesn't burn out, you must begin with a *mixture* of ice and water. *They must both be at 0°C, and you must know the mass of the ice and the water separately at the start.*

There are a number of ways to achieve this. One procedure is given, but you can probably think of a better way.

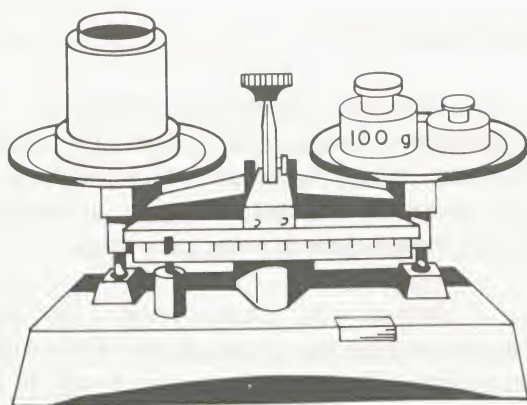


Figure 13.

1. *Precool the thermos bottle.* Pour ice water into the thermos bottle to cool it down to the starting temperature of 0°C . You don't want it to contribute to the heat input to the ice and water mixture. When it is cool pour out the ice water.

2. *Place the cold (dried) thermos bottle on a balance* and adjust it to exactly balance. Record the mass.

3. *Pour in about 100 g of ice-cold water.* Be sure that the water is at 0°C and includes no ice.

Measure and record the new mass.

4. *Put in about 200 g of crushed ice.*

Be sure that the ice is relatively dry.

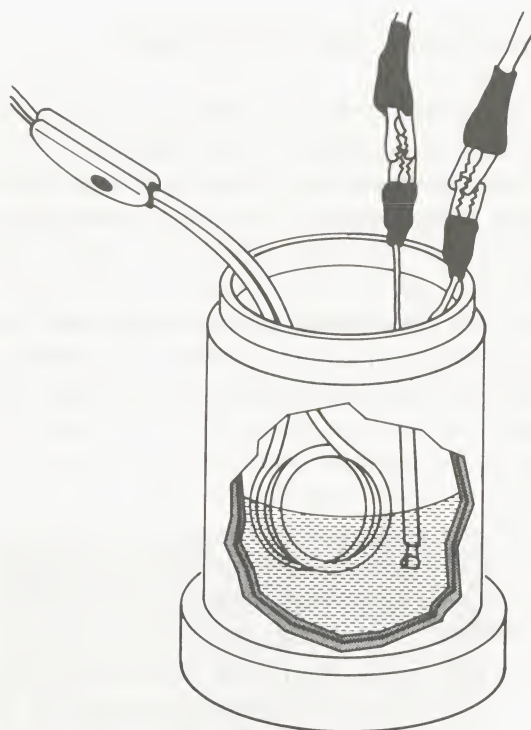
Measure and record the new mass.

Making the Measurement

1. *Place the immersion heater and thermistor deep into the ice-water mixture.*

The situation at $t = 0 \text{ s}$ ($T = 0^{\circ}\text{C}$) should look like that in Figure 14. You must move quickly after the initial mass has been determined so that very little melting occurs.

2. *Record the initial thermistor resistance* in the table provided on the data page.



$T = 0^{\circ}\text{C}$

100g Water

200g Ice

Figure 14.

This resistance should correspond to 0°C on your calibration scale.

3. *Simultaneously turn on the heater power supply and stopwatch.* Take thermistor resistance readings every 30 seconds. Use the "Notes" column to record the time at which all of the ice is melted and the time at which the water starts to boil. Stir the water frequently to be sure it is at a uniform temperature.

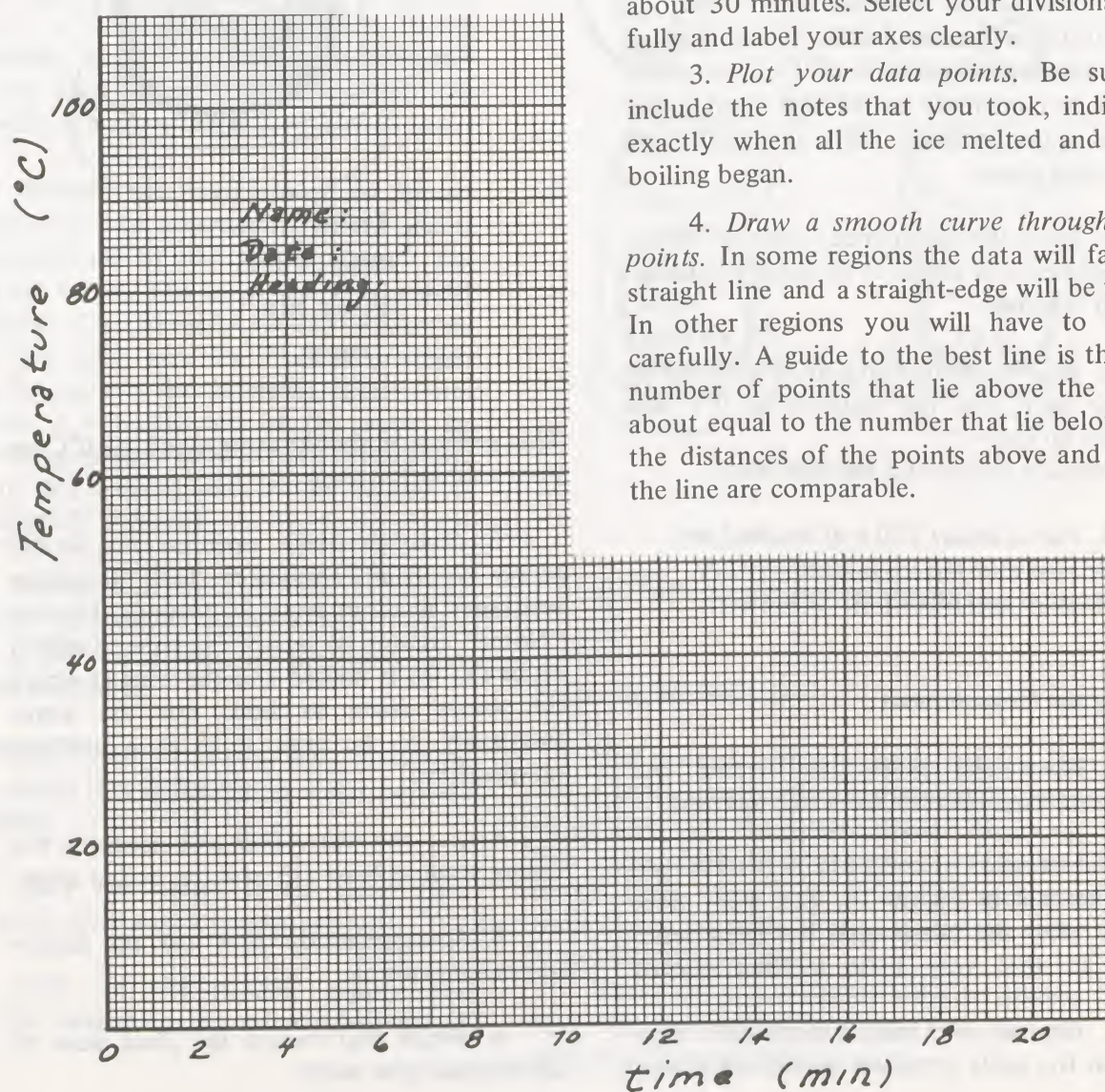
4. *Let the water boil* and continue the timing until at least $1/3$ of it has boiled away.

5. *Simultaneously turn off the heater and the stopwatch.*

6. *Weigh and record the final mass* of the thermos plus water.

ANALYSIS OF THE EXPERIMENT

Now that you have taken your data, the next step is to display it in such a way that you can easily see what was going on. A graph of the temperature of the water versus time will do that for this experiment. From the graph you will be able to analyze more easily what was happening at each stage, and to calculate the amount of energy required to change the water from one phase to another phase.



Graphing the Data

1. *Convert thermistor resistance to temperature.* Using your calibration scale, determine the temperature corresponding to each thermistor resistance you measured. Record these values in your data table.

2. *Prepare the graph paper.* For this experiment plot the temperature of the water versus time. The most convenient way to do this is to put temperature on the y-axis. The range of temperature will be from 0°C to 100°C. The range for time will be from 0 to about 30 minutes. Select your divisions carefully and label your axes clearly.

3. *Plot your data points.* Be sure to include the notes that you took, indicating exactly when all the ice melted and when boiling began.

4. *Draw a smooth curve through your points.* In some regions the data will fall in a straight line and a straight-edge will be useful. In other regions you will have to sketch carefully. A guide to the best line is that the number of points that lie above the line is about equal to the number that lie below, and the distances of the points above and below the line are comparable.

Understanding the Graph

What is the graph that you have drawn? Experimentally you observed that, as energy was supplied at a constant rate, the ice first melted to water, the water then heated up, and finally it began to boil. In a graph of temperature versus time, this constant rate of putting in energy results in first a flat region, indicating that the temperature of the melting ice stays the same until it is all melted. Then the graph slopes upward as the water is heated. Finally, there is another flat region because the boiling water stays at a constant temperature.

Figure 15 is a graph of an idealized experiment on water over a considerably wider range of temperature. It illustrates what would have happened if you had started with ice that was extremely cold, had continued to

supply energy until all of the water was converted to steam, and had continued to heat the steam. To perform such an experiment would require rather sophisticated apparatus and techniques. Your simpler experiment covered only the unshaded region.

The Graphs for Other Substances

If you could have performed a similar experiment on a substance other than water, you would have obtained a graph that looked much like the one shown. There would be differences in temperatures and in lengths and slopes of lines but the general character of two flat regions separating three upward sloping lines would be the same. Further, the description of what was happening would have been much like that for water.

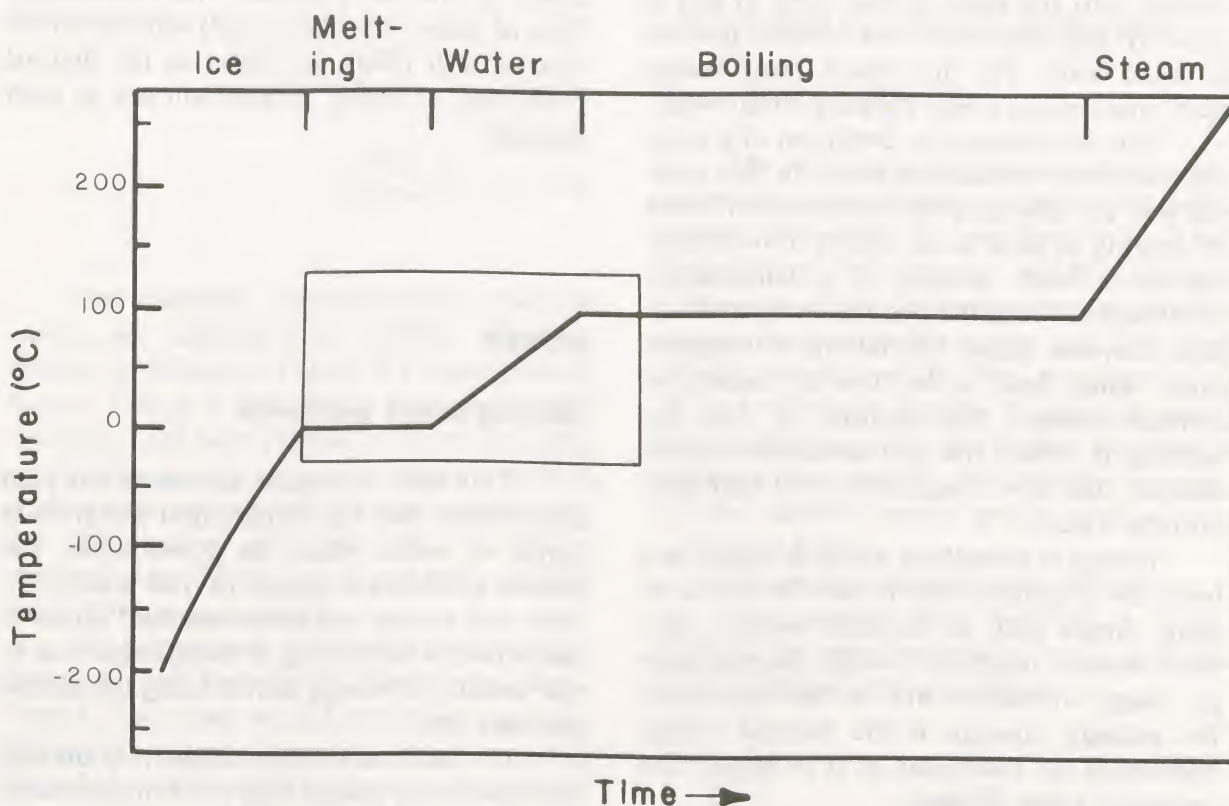


Figure 15.

ENERGY

What Is Energy?

The next step is to determine how much energy was required to raise the temperature in each of the various phases or to cause phase changes. To do this we must be certain of what is meant by energy. We all have some “feel” for what energy is and the term is used or heard frequently. But energy is not an easy quantity to define or describe precisely. Take a moment and try to answer the question, “What is energy?”

Now that you appreciate the problem, let us attempt to define energy. *Energy* is a property of a physical system. Energy depends *only* on the specific condition or state of a system and it does not depend on how the system got into that condition. To change the condition of a body, such as its temperature, you have to transfer energy from the outside into the body or vice versa. If this is done by applying forces, the transfer process is called *work*. For this reason many books state that energy is the capacity to do work.

You can change the condition of a body without doing mechanical work. In this module you are changing the condition of water by heating it. *Heat* is the energy flow into or out of a body because of a temperature difference between the body and its surroundings. *Thermal* means “pertaining to temperature.” Thus, *heat* is the flow or transfer of *thermal energy*. The melting of ice, the heating of water, and its vaporization are all changes that are brought about by heat flow into the water.

Energy is something which is stored in a body or a system, and it can be stored in many forms such as chemical energy, electrical energy, magnetic energy, thermal energy, energy of motion, etc. In this experiment the primary concern is the thermal energy transferred to the water as it is heated and undergoes phase changes.

Measuring Energy

Energy is a *conserved* quantity. That is, it cannot be created or destroyed. It can only be *transformed* from one kind of energy to another, or *transferred* from one system to another. In your experiment the electrical energy put into the heater was transformed into thermal energy which then was transferred as heat into the water.

Energy is such an important quantity that we must have a way of measuring it, so we can answer the question, “how much?” There is no way of measuring how much total energy resides in a body. But how much energy is transferred (or transformed) can be measured.

The Standard International (SI) unit for energy is the *joule* (J). It is defined in terms of a mechanical transfer process. But there are other energy units; many of them arose before the relationship between different kinds of transfer processes was understood. Two of these, the *calorie* (cal) and the *British thermal unit* (Btu), are based on the thermal properties of water, as you will see in your analysis.

POWER

Relating Energy and Power

You need a measure of energy for your experiment. But the energy input was given in terms of watts, which are power units. The heater produced a power of 160 watts (W). How are energy and power related? *Power is the rate at which energy is transferred*; that is, the amount of energy that is being transferred per unit time.

In most practical situations it is the rate of transferring energy that is of interest since

the total energy transferred will depend on how long the transfer process goes on. Most systems specify a power rating (the amount of energy they transfer per unit time). This is particularly true of electrical devices: electric motors, light bulbs, an immersion heater, and so on. The power for these items is given in terms of watts. *One watt (W)* is a unit of electric power *equal* to a rate of energy transfer of *one joule per second* (J/s).

Calculating Energy from Power

If the power is constant it is a simple matter to obtain the total energy transferred during a given period of time.

$$\text{Energy transferred} = \text{power} \times \text{time}$$

$$= \left(\frac{\text{energy}}{\text{time}} \right) \times \text{time}$$

For example,

$$\text{Joule} = \text{watts} \times \text{seconds}$$

$$= \left(\frac{\text{joule}}{\text{second}} \right) \times \text{seconds}$$

For example, electric utilities charge so much per kilowatt-hour (kWh), which is power in kilowatts (1000 W) times time in hours. This is a measure of how much total energy is used over a period of time. The units are a little strange since one kilowatt (kW) is 1000 joules per second and you multiply this by the number of *hours*. But if this is multiplied by 3600 seconds per hour you will have the energy in joules.

In Experiment A-2 the electric power input to the immersion heater was determined. The power should have been constant. Since you want to know how much energy Q it took to produce various results (to melt all

the ice; to raise the water from 0°C to 100°C; to boil away x number of grams of water) simply multiply the time (t) it took for the process by the input power P . (Figure 16.)

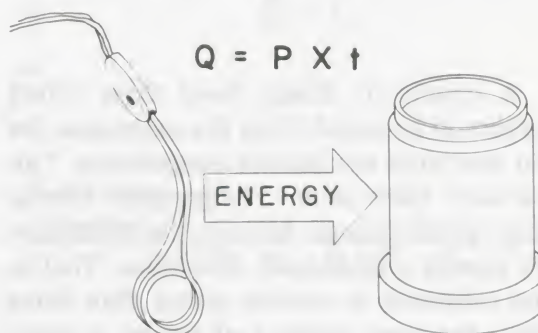


Figure 16.

THE THERMAL ENERGY OF WATER

Some Energy Definitions

The next step is to explore the concept of energy as it relates to your experimental results. The graph of your data showed two distinct types of processes: (1) the heating of a phase in which the temperature increased as energy flowed into the water, and (2) a phase change, during which the temperature remained constant despite a constant energy input. The amounts of energy required to produce these results are similarly expressed by two distinct terms, *specific heat capacity* and *latent heat*.

These terms are defined as follows:

The specific heat capacity c is the amount of energy required to heat a unit mass m of a substance by one degree:

$$c = \frac{Q}{m\Delta T}$$

Here, Q is the energy added, m is the mass of the substance and ΔT^* is the *change* in temperature.

The latent heat L is the amount of energy required to convert a unit mass of a substance from one phase to another:

$$L = \frac{Q}{m}$$

A couple of things about these definitions should be noted. First the expression for latent heat does not include temperature. This is because there is no temperature change during a phase change. Second, the definitions work equally well in both directions. That is, if the substance is cooling rather than being heated, the same amount of energy is given off rather than having to be supplied.

Energy Units and the Specific Heat Capacity of Water

If we choose water as the substance that is being heated, two common units of energy can be defined. In either case, the specific heat capacity of water is set to be one. If the mass of the water is in *grams* (g) and the temperature change in *degrees Celsius* ($^{\circ}\text{C}$), the unit of energy which results is the *calorie* (cal). The specific heat capacity of water is thus $1 \text{ cal/g}^{\circ}\text{C}$. (We should point out that the “calorie” which is used to measure the energy content of food is actually a *kilocalorie* (kcal), or 1000 cal. Thus, the average American, on a “3000 calorie diet,” consumes 3,000,000 cal, enough energy to raise the temperature of 30 kg of water from the freezing point to the boiling point.)

In the English system of units, the water is measured in pounds (lb), and the temperature in *degrees Fahrenheit* ($^{\circ}\text{F}$), resulting in

*The Greek letter *delta* (Δ) is often used to indicate a change or difference in a quantity. Thus ΔT is the change in temperature when energy Q is added.

the energy unit of *British thermal unit* (Btu). In this system, the specific heat capacity of water is $\text{Btu/lb}^{\circ}\text{F}$.

In the SI system of units, the specific heat capacity of water is $4.2 \text{ J/g}^{\circ}\text{C}$.

APPLYING THE DEFINITIONS TO YOUR DATA

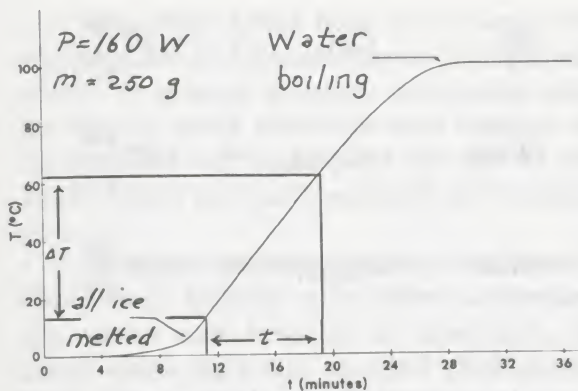
From your experimental data you can calculate the amount of energy used to raise a known mass of water by one degree. The *specific heat capacity* of water can be experimentally determined and compared to these definitions.

You also know how much energy you put in to convert a certain mass of ice into water and a certain mass of water into steam. From this you can determine the *latent heat of melting* and the *latent heat of vaporization* for water. Follow the procedure described and illustrated to get the results. Record these results on the data page.

Specific Heat of Water

1. Calculate the specific heat capacity of water from your data. The upward sloping section of the curve represents the heating of the water. But you should only use the *linear* or straight line, portion of the curve for your calculation. When the curve is linear the water is being heated uniformly. When it is no longer a straight line some non-uniform heating is going on. For example, as the water approaches the boiling point, the curve starts to bend. This means that the water around the heater is already boiling.

Since the power is in watts, the specific heat capacity will come out in $\text{J/g}^{\circ}\text{C}$. To compare your results with the definition of the calorie use the fact that $1 \text{ cal} = 4.2 \text{ J}$ (see the Energy Unit Table at the end of the section). Under ideal conditions 1.00 calorie would be required to heat 1 g of water by 1°C .



Energy supplied = power \times time

$$\begin{aligned}
 Q \text{ (J)} &= P \text{ (W)} \times t \text{ (s)} \\
 &= 160 \text{ W} \times (19 - 11) \text{ min} \times \frac{60 \text{ s}}{\text{min}} \\
 &= 76,800 \text{ J}
 \end{aligned}$$

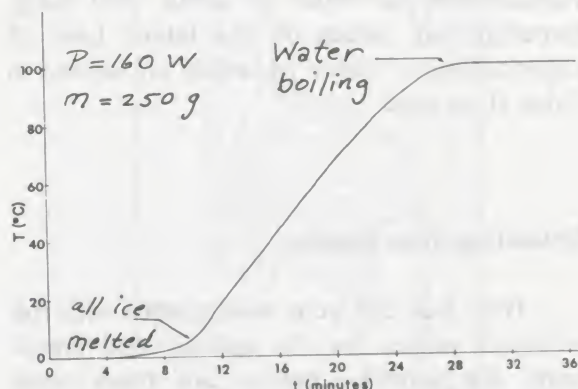
Specific heat capacity = $\frac{\text{energy supplied}}{(\text{mass}) \times (\text{temperature change})}$

$$\begin{aligned}
 c \left(\frac{\text{J}}{\text{g}^{\circ}\text{C}} \right) &= \frac{Q \text{ (J)}}{m \text{ (g)} \times \Delta T (^{\circ}\text{C})} \\
 &= \frac{76,800 \text{ J}}{250 \text{ g} \times (61^{\circ}\text{C} - 13^{\circ}\text{C})} \\
 &= \frac{76,800 \text{ J}}{12,000 \text{ g}^{\circ}\text{C}} \\
 c &= 6.4 \text{ J/g}^{\circ}\text{C}
 \end{aligned}$$

Heat of Melting

2. Calculate the latent heat of melting from the data. In taking the data it was suggested that you make notes about what was happening and when. One thing you should have noted was the exact time that all the ice disappeared. Using this time you can

determine the amount of energy required to melt the initial mass of ice and thus determine the value of the latent heat of melting.



$$\begin{aligned}
 Q &= Pt \\
 &= 160 \text{ W} \times 10 \text{ min} \times \frac{60 \text{ s}}{\text{min}} \\
 &= 96,000 \text{ J}
 \end{aligned}$$

$$\begin{aligned}
 L &= \frac{Q}{m_{\text{ice}}} \\
 &= \frac{96,000 \text{ J}}{250 \text{ g}} \\
 &= 384 \frac{\text{J}}{\text{g}}
 \end{aligned}$$

Again convert your results into calories by using the conversion factor. The accepted value for the latent heat of melting ice is about 80 cal/g.

Heat of Vaporization

3. Calculate the latent heat of vaporization from the data. This can be calculated in exactly the same manner as that for the latent heat of melting. The mass to use is the mass of water that was boiled away by the energy put in during the boiling period. This

is simply the difference between the initial mass of ice plus water minus the final mass of water.

The accepted value for the latent heat of vaporization of water is about 540 cal/g. Experimental values of the latent heat of vaporization of other materials are shown in Table II on page 25.

Evaluating Your Results

How well did your results agree with the accepted values for the specific and latent heats for water? Chances are there were significant differences. In the sample calculations a value of 1.5 cal/g°C was obtained when the true value is, by definition, 1.00 cal/g°C.

The results indicated that it took about 1.5 times as much energy to raise the temperature of the water by 1°C as it should have. Why did it take so much more energy? Can you think of possible reasons why this was so? Do you think you could improve on the experimental design to obtain a more accurate value for the specific heat of water? One of the objectives of experimental physics is to do just this; design experiments that give very accurate values for basic physical quantities.

COMPARING MAGNITUDES OF THE ENERGIES

The Specific Heat Capacities

One can obtain values for the specific heat capacities of ice and steam by performing experiments similar to the one with water. The following table gives the accepted values for these quantities. These are the amounts of energy required to raise the temperature of 1 g of the water in that phase by 1°C.

Ice	c_{solid}	=	$.50 \frac{\text{cal}}{\text{g}^\circ\text{C}}$
Water	c_{liquid}	=	$1.00 \frac{\text{cal}}{\text{g}^\circ\text{C}}$
Steam	c_{vapor}	=	$.48 \frac{\text{cal}}{\text{g}^\circ\text{C}}$

In comparing the three specific heats, the first thing to notice is that the values for the three phases of water differ only by about a factor of two. Despite the fact that the properties of ice, water, and steam are quite different, the amount of energy required to raise the temperature of one gram of any one phase by 1°C is about the same as for any other phase.

What does this mean? One interpretation is that there may be some fundamental relationship between the energy change and the temperature change that does not depend on the phase. While this is hardly a proof, other evidence does confirm this observation.

The Latent Heats

The two latent heats on the other hand are not only quite different but both are huge compared to the specific heats. For example, it takes more than five times as much energy to vaporize 1 g of water as it does to raise its temperature from the freezing point to the boiling point. Phase changes are associated with considerable energy changes. If the phase change is to a higher temperature phase, then the energy must be supplied. If it is to a lower temperature phase that same amount of energy will be released.

Ice Melting (Water Freezing)	L_m	=	$79.7 \frac{\text{cal}}{\text{g}}$
Water Vaporizing (Steam Condensing)	L_v	=	$540 \frac{\text{cal}}{\text{g}}$

Why these latent heats are so large and why they are so different cannot be explained simply. In general, however, it has to do with the way in which molecules bind together to form solids and liquids and the size of the forces which hold each molecule to its neighbors.

Now the question remains, "So what?" Other than helping us to better understand the nature and behavior of substances, do these values have any practical significance? The answer is a strong "yes," in many important ways.

APPLICATIONS

At the beginning of this section it was stated that water is about the only substance that undergoes phase changes at temperatures near those that occur naturally on earth. Now you have seen that considerable energy is involved in phase changes. Putting these two facts together, and adding the abundance of water, man has found many ways to exploit these phenomena in his technologies.

Air Conditioning

Evaporation is a phase change which is much like boiling. (This will be studied in more detail in Section C.) As in boiling, the latent heat of vaporization must be absorbed for each gram of water that evaporates. This heat is supplied by the water itself, and so when some of the water evaporates, the remaining water is cooled. Air conditioning systems of large buildings utilize this principle in cooling towers in which water is made to flow over large surface areas which are exposed to the air. (Figure 17.) As some of the water evaporates the remaining water is cooled by the loss of the large latent heat of vaporization.

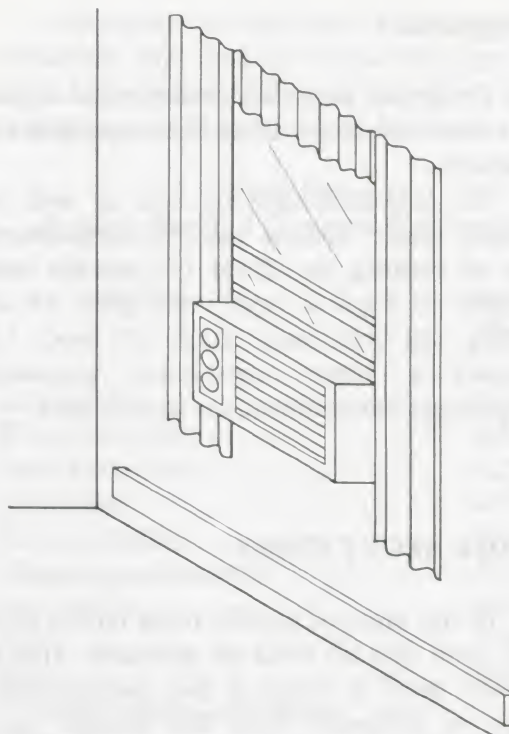


Figure 17.

Heating Buildings

A basic concern in northern climates is keeping buildings warm. This involves moving energy simply and cheaply.

Steam is one obvious solution. It can be easily moved in pipes. When steam condenses, it releases heat through its large latent heat of condensation, and the energy can be extracted by letting the steam condense in a radiator.

Since steam normally condenses at 100°C , steam heat is quite hot and can be hazardous in the home. Hot water is used more often for home heating. While the *specific heat capacity* of water is much less than the *latent heat* of steam, water is much more dense. Many more grams of the liquid can be circulated per second than of the vapor. The heat transported can be the same, but at a lower and therefore safer radiator temperature.

Refrigeration

Cooling of foods is also important. Again the latent heat and specific heat capacities are exploited.

The old-fashioned ice box as well as modern picnic coolers use the large latent heat of melting ice. Since the specific heat capacity of food is small, one gram of ice melting will cool many grams of food. Ice provides a cheap, temporary, constant-temperature environment for storing food.

A NOTE ABOUT TERMS

In the table of specific heats on the next page, note that no units are indicated. That is because what is listed is the *specific heat*, which is different from the *specific heat capacity*. Both specific heat and specific heat capacity are different from the *heat capacity*. These three terms are closely related in that they all refer to the amount of energy required to raise the temperature of a substance. But there are slight differences which often cause confusion. In the following two sections these differences are explained.

Specific Heat Capacity

The amount of energy required to heat a unit mass of a substance by one degree:

$$c = \frac{Q}{m\Delta T}$$

Units: $\frac{\text{J}}{\text{kg}^\circ\text{C}}$ (SI unit)

also $\frac{\text{cal}}{\text{g}^\circ\text{C}}$ or $\frac{\text{Btu}}{\text{lb}^\circ\text{F}}$

The specific heat capacity is the amount of energy required to heat a *unit mass* of substance. The units for specific heat capacity include the mass. This is the term used in the module and which you calculated from your data.

In two systems of energy units the specific heat capacity of water is defined as 1.000 cal/g°C or 1.000 Btu/lb°F.

Specific Heat

The ratio of the specific heat capacity of a substance to that of water (at 15°C):

$$s = \frac{c_{\text{substance}}}{c_{\text{water}}}$$

or: $c_{\text{substance}} = s \times c_{\text{water}}$

Units: None

The specific heat capacity is the specific heat times 1.000 cal/g°C or 1.000 Btu/lb°F. That is, simply tack on either set of units to the specific heat for a substance to get its specific heat capacity. However, this does not work when the energies are in joules.

In most practical situations, you will want to know how much energy it will take to raise the temperature of an object by one degree with a mass differing from one unit. This energy is called its *heat capacity*. The word *specific* was to specify unit mass only. To get heat capacity you simply multiply the specific heat capacity of the material by the mass of the object.

Heat Capacity

The amount of energy required to heat an object by one degree:

$$C = mc$$

$$= \frac{Q}{\Delta T}$$

Units: $\frac{\text{J}}{^\circ\text{C}}$ (SI unit)

also $\frac{\text{cal}}{^\circ\text{C}}$ or $\frac{\text{Btu}}{^\circ\text{F}}$

SPECIFIC AND LATENT HEATS OF OTHER SUBSTANCES

The specific and latent heats have been measured for the various phases and phase changes for most substances. However, since we generally encounter a substance in but one, or at most two, of its phases, it is only the data for these that are of common interest. For steel, for example, it is the specific heat of the solid that is important, and few people care about its latent heat of vaporization or the specific heat of the vapor.

Specific heats of a number of substances in their most common phases are shown in the tables below. Since *specific heat can vary with temperature*, we have given only the values for room temperature (unless otherwise indicated). For the specific heats at other temperatures consult the *Handbook of Chemistry and Physics*, Chemical Rubber Company.

Table II.
Latent Heats of Common Substances

Melting	Temperature of Change (°C)	Latent Heat Cal/g
Alcohol (Ethyl)	- 114	24.9
Ammonia	- 75	108.1
Mercury	- 39	2.8
Ethylene Glycol	- 12	42
Water	0	79.7
Tin	232	13.8
Lead	327	5.5
Aluminum	658	94
Sublimation		
Carbon Dioxide	- 78	158
Vaporization		
Ammonia	- 33	327
Acetone	56	125
Alcohol (Ethyl)	78	204
Water	100	540
Ethylene Glycol	197	191
Mercury	357	70.6

Also given are the latent heats for a few substances that undergo phase changes near room temperature. Compare the values given with those you have measured for water.

Table III.
Specific Heats of Common Substances

Solids	Specific Heat
Ice (at 0°C)	0.50
Wood (average)	0.42
Earth (dry clay)	0.22
Aluminum	0.21
Stone (granite)	0.19
Glass (approximately)	0.15
Iron (steel)	0.11
Zinc	0.093
Brass	0.092
(60% Copper—40% Zinc)	
Copper	0.092
Silver	0.056
Gold	0.031
Lead	0.031
Liquids	
Ammonia	1.1
Water	1.00
Alcohol (Ethyl)	0.58
Ethylene Glycol	0.57
Acetone	0.53
Olive Oil	0.47
Sulphuric Acid	0.34
Carbon	0.20
Tetrachloride	
Mercury	0.033
Vapors (at constant pressure)	
Hydrogen	3.4
Helium	1.3
Steam (@100°C)	0.48
Nitrogen	0.25
Air	0.24
Oxygen	0.22
Carbon Dioxide	0.20
Argon	0.125

ABOUT THE THERMISTOR (OPTIONAL)

In this section the behavior of the thermistor is briefly described in order that you may better understand the manufacturer's scale that relates thermistor resistance to temperature. It is beyond the scope of this module to describe its behavior in terms of the theory of solid-state physics. But the results of the theory can be given as an explanation of how the manufacturer's scale was developed and show how it can be reproduced for any thermistor.

A thermistor is a ceramic material made by heating without melting (*sintering*) mixtures of metallic oxides such as manganese, nickel, cobalt, copper, iron and uranium. The resulting materials are called *semiconductors* and are selected because of their large, *negative temperature coefficient of resistance*. This means that as the temperature goes up, the resistance goes down, and that the resistance changes are large for small temperature changes. Thermistors come in a variety of sizes and shapes to serve specific technical applications.

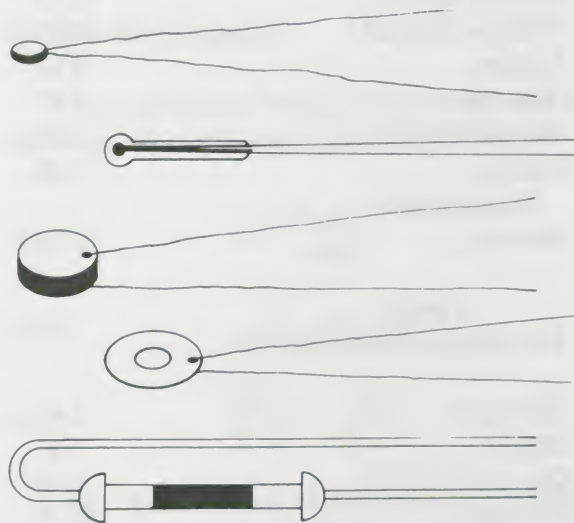


Figure 18. Various Thermistor Shapes.

Calibration Equation

The relation between resistance and temperature for thermistors can be described quite accurately by the mathematical equation:

$$\log R = .434 \beta \frac{1}{T} + b$$

Here β is a constant which depends on what material the thermistor is made of. It is β that manufacturers try to adjust to make thermistors which are accurate and sensitive in various temperature regions. The term b is a less important constant which we will discuss later.

Calibration Graph

This equation is important for thermistor calibration. It has the form of the equation of a straight line, $y = mx + b$, if we define $y = \log R$, $x = 1/T$, the slope $m = .434 \beta$ and the constant $b = b$. The equation means therefore, that *if you plot $\log R$ against $1/T$ you should get a straight line*. Since two points are all that are needed to determine a straight line, only two pairs of R and T are needed to draw the calibration graph.

The following describes how to draw the calibration graph from your data. You will see whether plotting $\log R$ versus $1/T$ does give a straight line, and how your results relate to the manufacturer's scale.

MAKING THE THERMISTOR CALIBRATION GRAPH

In the expression $\log R = .434 \beta (1/T) + b$, R is the thermistor resistance in ohms and T is the *absolute* temperature in kelvins. You will learn more about the absolute temperature scale in Section B, but for the moment simply follow the procedure to get T in kelvins (K).

Only two points are needed to determine a straight line. Since small errors do sometimes occur in measurement, use several points to obtain the best straight line. Use the thermistor resistances and mercury thermometer temperatures taken when the two were compared.

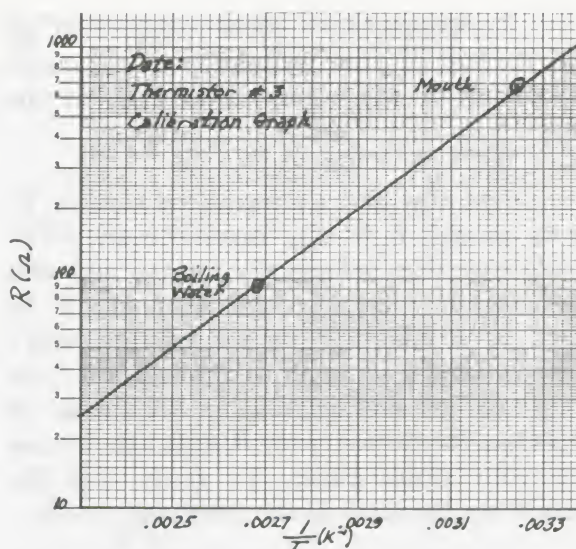
Procedure

1. *Convert from °C to K.* The temperature you use must be absolute temperature (K). To get K from °C simply add 273 to each of your temperature readings.

2. *Calculate $1/T$.* Since $\log R$ is proportional to $1/T$ you must calculate $1/T(K)$ for each of your four values. A calculator will help considerably in doing this.

Thermometer Temperature	Temp (K)	$\frac{1}{T(K)}$

3. *Plot R versus $1/T$ on semi-log paper.* Rather than looking up $\log R$ for each value of R it is more convenient to use *semi-log paper*. Semi-log paper has logarithmically spaced lines on the y-axis but linearly spaced lines on the x-axis. At least 3 cycles on the log axis will be needed and a range of $1/T$ from .0023 to .0037. Label your graph paper and plot your values.



Sample student graph.

4. *Draw a straight line through your points.* The mathematical expression says that these points should lie in a straight line. Therefore, draw a straight line through the points. In general this means that the number of points that lie above the line should equal the number that lie below, and their distances above and below the line should be about equal.

COMPARING YOUR GRAPH TO THE MANUFACTURER'S SCALES

The next step is to compare your graph to the manufacturer's scale. Since this scale has temperatures in °C, you need to relate your $1/T(K)$ scale to $T(^{\circ}C)$.

1. *Make a table of values of $1/T(K)$ for every 10°C from 0°C to 140°C.*

$T(^{\circ}C)$	$T(K)$	$\frac{1}{T(K)}$	R

2. Plot and label these values of $T(^{\circ}\text{C})$ on the top of your calibration graph, corresponding to the values of $1/T(\text{K})$ at the bottom, as shown below.

You now have a temperature scale in $^{\circ}\text{C}$, even though it is only marked every 10°C . Note that it is not equally spaced, and that temperature increases from right to left. In fact, it is identical to the manufacturer's temperature scale. One of the scales is T in $^{\circ}\text{C}$, but spaced according to intervals of $1/T(\text{K})$. The other is a $\log R$ scale like the one on your graph paper. To verify that the results are the same do the following.

3. Determine values of R from the manufacturer's scale for each of your values of T in $^{\circ}\text{C}$.

4. Plot these values on graph paper. They should all lie on or near your experimental curve. Do they?

RECALIBRATING THE THERMISTOR

The slope of the calibration graph is equal to $.434 \beta$. For most thermistors β is a

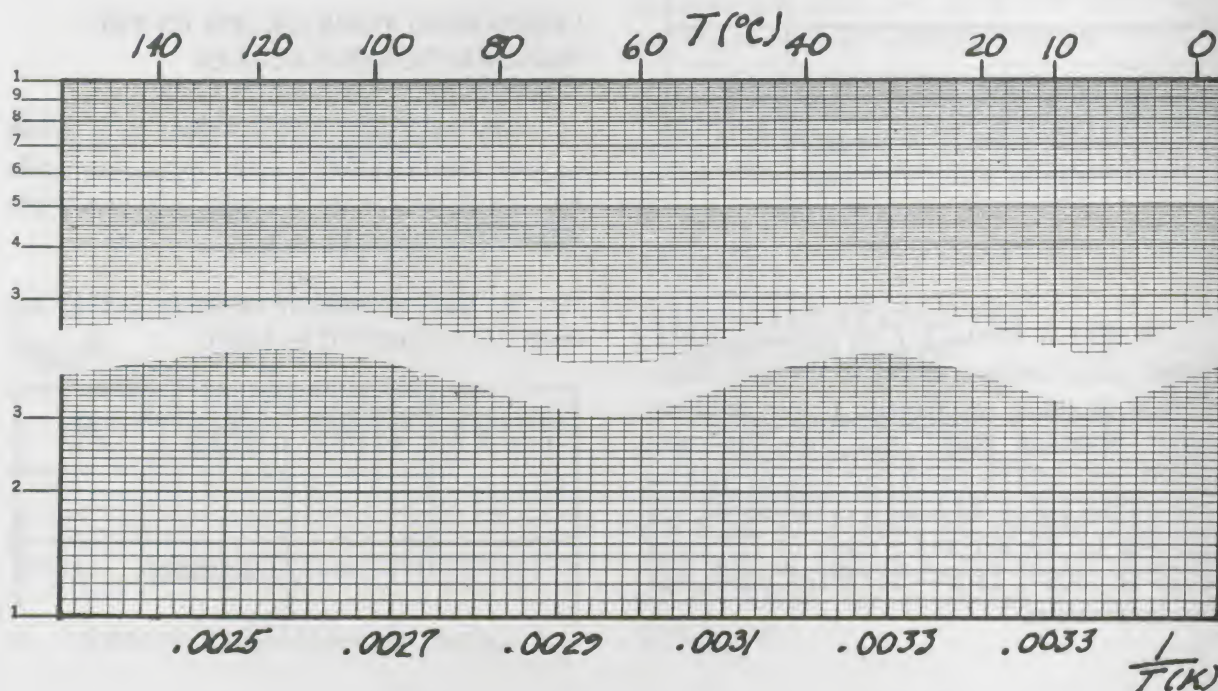
constant which does not change significantly from thermistor to thermistor, or with thermistor age. Once the slope of your calibration graph is determined, the slope will not change.

The constant b , however, does often change. b is the value of $\log R$ when:

$$\frac{1}{T} = 0$$

A change in b will simply move the line up and down on the paper without changing its slope. For the manufacturer's scale it simply means a right to left movement.

Since b may change, it is important to recalibrate your thermistor every time you use it. Recalibration is quite simple. Measure one pair of R and T values for your thermistor, say its resistance at room temperature, and plot that point on the graph. Then draw a line through that point with the same slope as your first line (parallel to your first line). This becomes your new calibration graph as in Figure 19. For the manufacturer's scale simply realign one scale relative to the other for the measured data points.



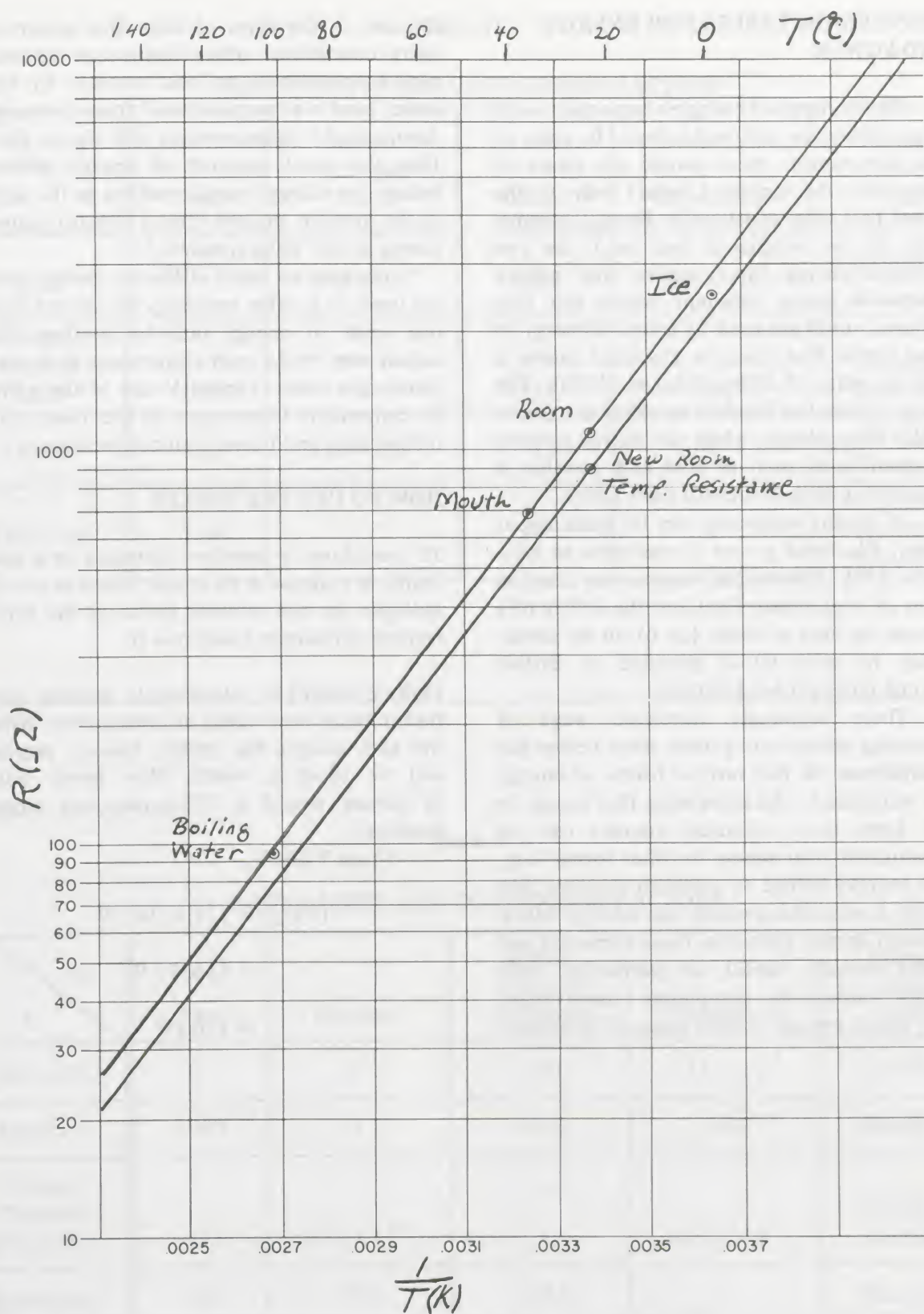


Figure 19.

CONVERSION TABLES FOR ENERGY AND POWER

The concept of energy is important to all areas of science and technology. In spite of this importance, most people are aware of energy (in the technical sense) only to the extent that they consume it. Energy is something to be purchased and used. As you consume energy, you realize that energy appears in many different forms and that different units are used to measure energy in these forms. For example, electrical energy is sold in units of kilowatt-hours (kWh). The energy content of foods is specified in calories (really kilocalories), while the energy content of other fuels such as coal and gasoline is measured in British thermal units (Btu).

A similar statement can be made about power. Electrical power is marketed in kilowatts (kW). Automobile engines are rated in terms of horsepower (hp), but the ability of a furnace to heat a house (or of an air conditioner to cool it) is specified in British thermal units per hour (Btu/h).

These seemingly unrelated ways of measuring energy and power arose before the equivalence of the various forms of energy was recognized. The knowledge that energy in one form (e.g., electrical energy) *can* be transformed into energy in other forms (e.g., heat energy) helped to establish the idea that energy is something which can exist in many different forms. However, these forms are not always equally useful. In particular, heat energy cannot be completely transformed into other energy forms; some of it *always*

remains in the form of heat. But under the right conditions, other forms can be converted completely to heat energy. In that sense, heat is a “second-class” form of energy. Also, careful measurements will always show that the total amount of energy present before an energy transformation is the same as the amount present after a transformation; energy is said to be *conserved*.

Because so many different energy units are used, it is often necessary to convert from one kind of energy unit to another. The easiest way to do such conversions is to use a *conversion table*. Tables IV and V summarize in convenient form many of the most common energy and power unit conversions.

HOW TO USE THE TABLES

To transform a number expressed in a unit found in column A to a unit found in row B, multiply by the number found at the intersection of column A and row B.

FOR EXAMPLE: Automobile engines have traditionally been rated in horsepower. When the U.S. adopts the metric system, engines will be rated in watts. How many watts of power would a 175-horsepower engine produce?

From Table V,

$$175 \text{ hp} = 175 \times 745 \text{ W}$$

$$= 130375 \text{ W}$$

$$\approx 130 \text{ kW}$$

Table IV.

ENERGY UNITS AND CONVERSION FACTORS

$\begin{array}{c} B \\ \diagdown \\ A \end{array}$	Joule	British Thermal Units	Calorie	Kilocalorie	Primary Areas Used
Joule	1	9.48×10^{-4}	.239	2.39×10^{-4}	Mechanical Electrical
British Thermal Unit	1055	1	252	.252	Thermal Chemical
Calorie	4.19	3.97×10^{-3}	1	10^{-3}	Thermal Chemical
Kilocalorie	4186	3.97	10^3	1	Chemical Nutrition Biological

Table V.

POWER UNITS AND CONVERSION FACTORS

$\begin{array}{c} B \\ \diagdown \\ A \end{array}$	Watt	Kilowatt	British Thermal Unit/hour	Horsepower	Primary Areas Used
Watt (J/s)	1	10^{-3}	3.41	1.34×10^{-3}	Electrical
Kilowatt	1000	1	3410	1.34	Electrical
British Thermal Unit/hour	.293	2.93×10^{-4}	1	3.93×10^{-4}	Thermal Chemical
Horsepower	745	.745	2544	1	Mechanical

REVIEW: Summary of Section A

Many (but not all) substances occur in three distinct *phases*—*solid*, *liquid*, and *vapor* (or *gas*). Phase changes involve energy changes. The phase changes of *melting* and *vaporization* require the addition of energy. The reverse processes, *freezing* and *condensation*, release energy.

Water is important and interesting for a number of reasons. It is essential to living organisms, it is the most common liquid, and it is the only substance found naturally in all three of its phases. The boiling and freezing temperatures of water (and other substances) depend on the pressure. The usual values apply only at one atmosphere of pressure.

Experiment A-1 was a measurement of the energy required to heat substances and cause phase changes. Water was chosen because of the convenient temperatures of its phase changes. A *thermistor*, which responds to a temperature change by undergoing a change in its resistance, was used to measure the temperature of the water in the experiments. The negative coefficient of resistance of a thermistor means that as its temperature goes up its resistance goes down.

Calibrating the thermistor means finding the temperatures that correspond to various resistance values. For a thermistor, $\log R$ is proportional to $1/T$ plus a constant where T is the absolute temperature in kelvins. Such a relation is a straight line on *semi-log* graph paper, and this property can be used to make a simple calibration scale.

Energy is a physical property that can be stored in a body. It can be stored in several forms, such as *chemical* energy, *electrical* energy, *magnetic* energy, *thermal* energy, energy of *motion*, etc. Energy transferred by mechanical means from one body to another is called *work*. Energy which is transferred from one body to another because of a temperature difference is called *heat*. In Experiment A-2, electric energy was supplied to the water by an immersion heater. Electrical energy supplied by the heater was changed into thermal energy of water.

Power is the rate of transferring energy. When energy is being transferred at the rate of one *joule per second* the power is one *watt*. Electrical power input to the immersion heater is found by measuring the applied *voltage* and heater *resistance* and using the relation:

$$P = \frac{V^2}{R}$$

When energy is being supplied at a constant rate (constant power), the *total* energy supplied is:

$$Q = P \times t$$

Two important thermal properties of matter are the *specific heat capacity* and the *latent heat*. Specific heat capacity is the energy required to raise the temperature of a *unit mass by one degree*. The specific heat capacity of water is used to define the *calorie* and the *Btu*.

Latent heat is the energy required to produce a phase change in a unit mass. Latent heats are quite large compared to specific heats. This is because phase changes involve major rearrangements of the atoms and the molecules of a substance. The large latent heats for water have many applications in heating and refrigeration systems.

QUESTIONS

1. Which of the following units are *not* units of energy?

- a) British thermal unit
- b) calorie
- c) watt
- d) kilocalorie
- e) joule

2. Some older pressure cookers had a safety device consisting of a metal plug in the top which melted if the pressure in the cooker became too high, thus releasing the pressure. Using an appropriate reference book (for instance, the *Handbook of Chemistry and*

Physics, Chemical Rubber Company), can you find a metal which would be appropriate to use for such a plug?

3. When you heated the water, the temperature rose steadily to 100°C . The temperature then stopped rising. Explain briefly why this happened.

4. How is *power* different from *energy*?

5. What is the difference between *specific heat capacity* and *latent heat*?

PROBLEMS

1. Calculate the energy required (in cal) to raise the temperature of 100 g of brass

from room temperature (20°C) to its melting point (900°C).

2. How much heat is released if 10 g of ammonia gas condense to form liquid ammonia?

3. A certain electric motor is rated at one horsepower (about 750 W). How many joules of work can it do in two minutes?

4. A certain lamp uses electric energy at the rate of 250 W. How long will it take the lamp to use a kWh?

5. How many joules of energy are required to boil away a cup of water (250 g) which starts at a temperature of 20°C ?

Section B

The Gas Phase

INTRODUCTION

In this section a household pressure cooker is used to learn about some important features of the behavior of gases. The pressure cooker is used because it is a convenient device that can be made airtight and that can stand fairly high temperatures and pressures.

Thousands of effects and devices can be understood only in terms of the behavior of the gaseous form of matter. For example, thunderstorms, hurricanes, and daily weather conditions depend upon the properties of air and water vapor. What is called weather is really a continually changing set of values for air temperature, air pressure, air volume, and quantity of water vapor.

The Familiar Behavior of Gases

The usefulness of an automobile tire depends in part upon the fact that forcing more air into it raises the pressure.

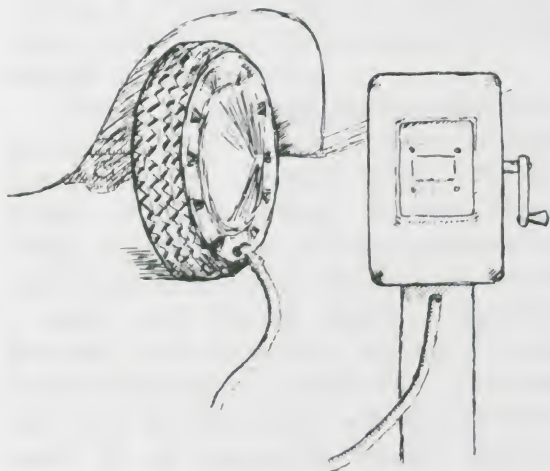


Figure 20.

The standard scuba air tank has a capacity of 71.2 ft^3 of air, but actually it is a cylinder only six inches in diameter and 24 inches in length. The volume of such a cylinder is less than half a cubic foot. How can it hold more than 71 ft^3 of air?

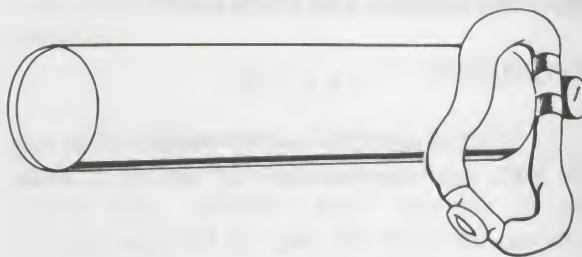


Figure 21.

The answer is that 71 ft^3 of air at ordinary atmospheric pressure can be forced into the small tank, but the pressure becomes enormously high, about 2200 pounds per square inch, or 150 times normal atmospheric pressure.

In the cylinder of a diesel engine the fuel-air mixture is forced into a small fraction of its original volume by the piston. This reduction in volume raises the pressure and it also raises the temperature to such a high value that the mixture ignites without a spark plug.

THE GENERAL GAS LAW

In all these situations and many others, we are concerned with what is called the "state" of the gas. When you ask what the state of a gas is, you are really asking a number of questions: how much gas is there (its mass or *number of molecules*, N)? What is the *pressure*, P ; what is the *volume*, V ? There

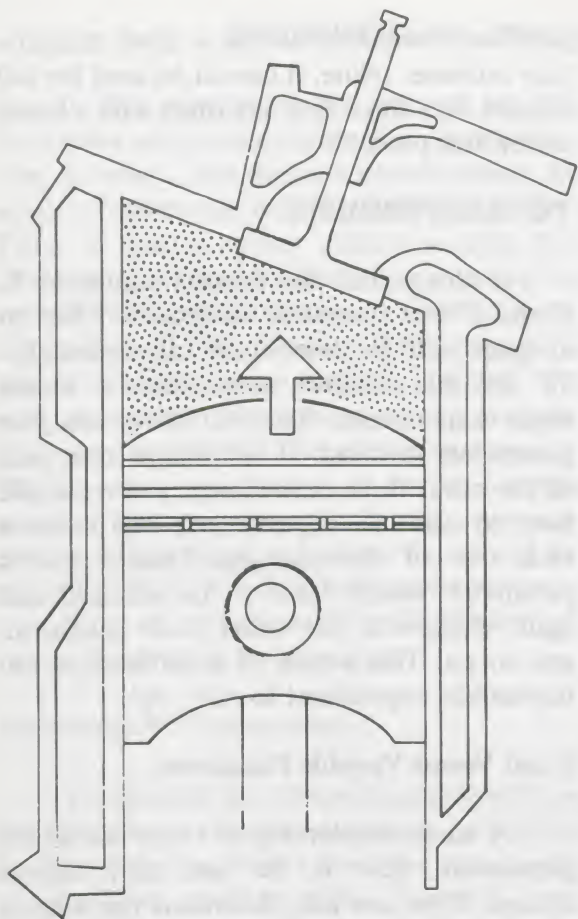


Figure 22.

can be other quantities to consider, but these are the key factors or *parameters* that describe the state of a sample of gas.

In this section the relation among these quantities will be investigated to see how N , P , V and T are related. This relation is summed up in an equation called the *General Gas Law*. In the experiment and the analysis that follows, the behavior of a gas will be studied and a statement of the General Gas Law based on your measured data will be developed.

Why Call the Law "General"?

The law is called "General" because it does not depend on the type of gas you are talking about. Regardless of what the gas is or

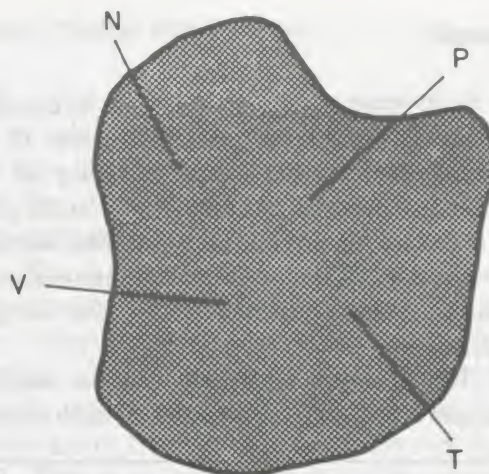


Figure 23.

even whether it is a mixture of several gases, the law can be applied equally well. For example, air is composed of about 78% nitrogen, 21% oxygen, and 1% other gases. If each one of these substances behaved differently with respect to a change in, say, the temperature, it would be an extremely difficult task to predict how the air as a whole would behave. However, since they all respond the same, the General Gas Law can be simply applied to the mixture, whatever it is.

When Can It Be Used?

Since the virtues of the General Gas Law have been explained a note of caution should be added. Other names for the law are the *Perfect Gas Law* and the *Ideal Gas Law*. These names are used because the law is not accurate over all the values of P , V and T that a gas can have. For example, just before a gas starts to condense to form a liquid this gas law no longer works. Only for an idealized or "perfect" gas would the General Gas Law hold under all possible conditions.

But provided that you are not too near the condensation temperature or at extremely high pressures these differences are not important. The General Gas Law is approximately correct for most situations you will be likely to encounter.

Example

Any time a closed container is exposed to heat, the pressure inside increases. If the pressure exceeds the strength rating of the container, then the container may burst causing a hazard to anyone around. The warning below is a typical one found on aerosol cans, cautioning the consumer about this danger. (Figure 24.)

The General Gas Law can be used to calculate the expected pressure in such *closed*,

EXPOSURE TO HEAT OR PROLONGED EXPOSURE TO SUN MAY CAUSE BURSTING. Do not puncture or throw into fire. Do not store in direct sunlight or automobiles. Store can in temperatures below 120°F.

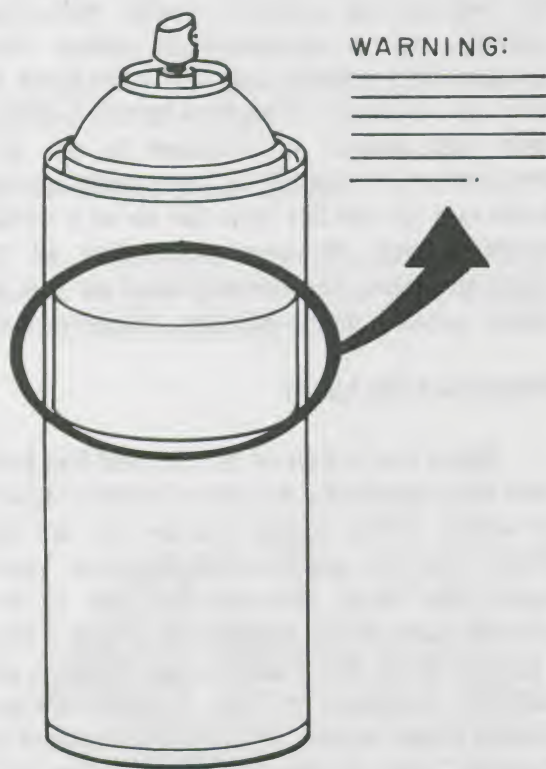


Figure 24.

gas-filled containers due to a given temperature increase. (Note, it cannot be used for *full* aerosol cans since they are filled with a liquid under high pressure.)

YOUR EXPERIMENT

In this section the relation among N , V , T and P that describes the general behavior of gases will be determined experimentally. To do this involves more than a simple single experiment. After all there are *four* parameters involved. If we change one, each of the other three may change, and we would have to carefully separate out and measure each one of the changes. Then a second parameter would have to be changed and again changes in the other three measured, and so on. This would be a difficult, if not impossible, experiment to carry out.

Fixed Versus Variable Parameters

A much simpler way is to *fix* two of the parameters, that is, be sure they cannot change. Then one may determine the relation between the remaining two (change the third and see how the fourth varies).

You will use the pressure cooker as a container with a *fixed volume*, and it will be carefully sealed so that no air molecules can get in or out—that is, there will also be a *fixed number of molecules*. You will then heat the pressure cooker to *change the temperature* of the air inside (measuring the temperature carefully with your thermistor) *and measure the changes in the pressure inside*.

After you have performed this experiment and analyzed the results, you will then examine other relations with which you are familiar. From these arguments an expression for the General Gas Law can be derived.

EXPERIMENT B-1. Measuring Pressure Versus Temperature

In this experiment the mass of gas and its volume will remain constant as its temperature is varied. The pressure cooker makes an ideal container for meeting these conditions. First, it has a rubber gasket so that the chamber may be sealed and no gas can leak in or out during the experiment. One of your first tasks will be to check that seal to be sure that it is leak tight, so that N is constant. We also assume that the volume of the pressure cooker is constant. (The aluminum expands slightly when it is heated, of course, but the resultant change in the volume of the pressure cooker will be small enough so that it can be ignored.) Thus, N and V will indeed be fixed.

Next the temperature and pressure of the air inside must be measured.

Measuring the Temperature

To measure the temperature you will use the thermistor that was calibrated in Section A. The pressure cooker has been fitted with an insulated, pressure tight, electrical feed-through so that you can place the thermistor inside the cooker and measure its resistance from outside. When attaching the thermistor, however, be sure that it does not touch the container walls. The container may become hotter than the gas during heating and damage the thermistor. Also, be careful that the clips attached to the thermistor leads do not touch each other, or you will have to open up and start over.

Measuring the Pressure

The pressure gauge which is attached to the pressure cooker is a *compound gauge*, meaning that it can be used for measuring pressures both above and below atmospheric pressure. (Pressures below atmospheric pressure are called "vacuum.") Since atmospheric pressure is marked 0, you will be measuring *gauge pressure*, not *absolute pressure*. This difference will be discussed later, but essen-

tially what it means is that your readings will all be relative to the atmospheric pressure of the day. Therefore, determine from a *barometer* the atmospheric pressure at the time of the readings.

To show you how confusing units can get, the divisions on the pressure gauge scale are different above and below atmospheric pressure. Those above zero are in terms of pounds per square inch (lb/in^2) while those below are in terms of inches of mercury (in Hg). This is a common convention in gauges so the manufacturers don't bother to mark the units on the scale. The units will be discussed later, but be sure to record which units you are reading for later use.



Figure 25. Compound pressure gauge.

The Experimental Set-Up

Figure 26 is a schematic diagram of a pressure cooker modified for measuring the P - T relation for a gas. The cooker is sealed by the rubber gasket. The hot plate is used to raise the temperature of the gas. The temperature is measured by the thermistor. The compound pressure gauge indicates the gas pressure. A pressure release is provided in case the pressure in the chamber becomes too great.

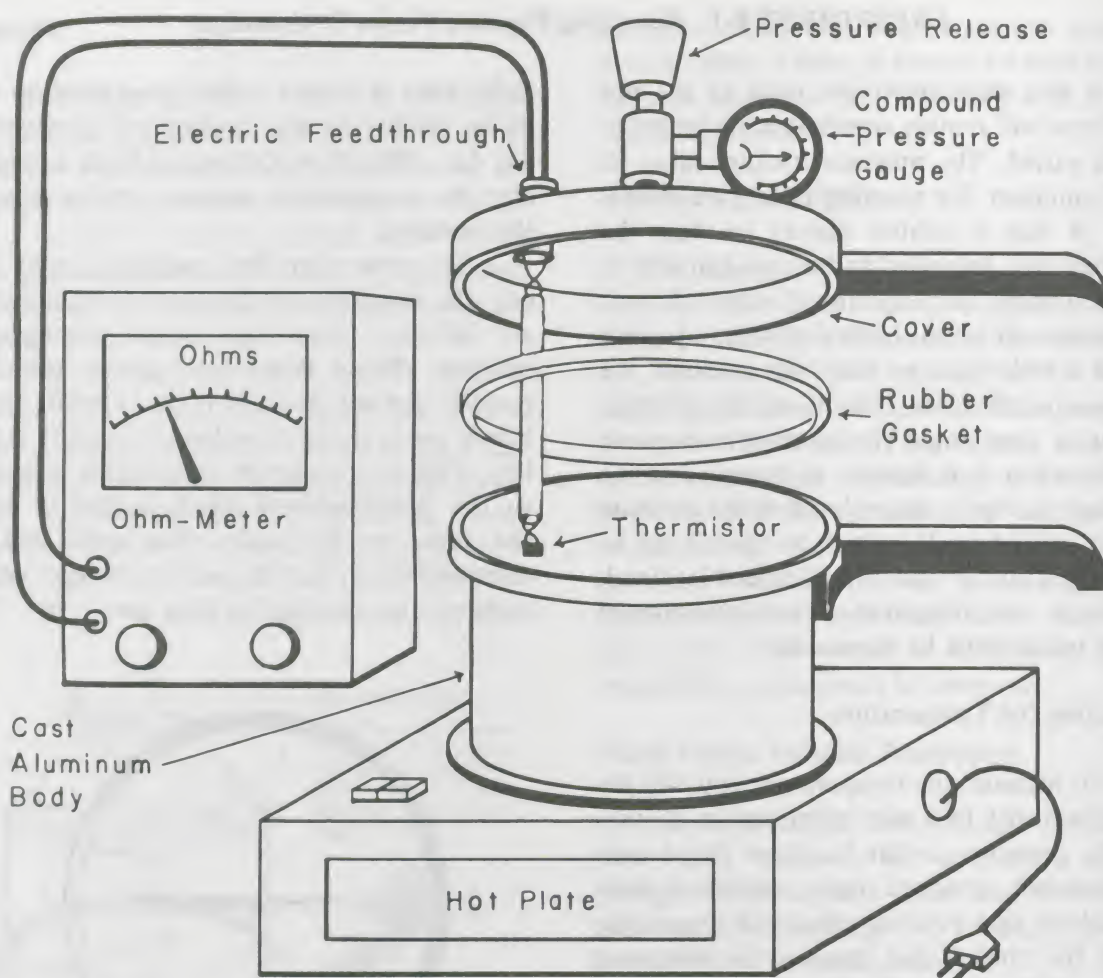


Figure 26.

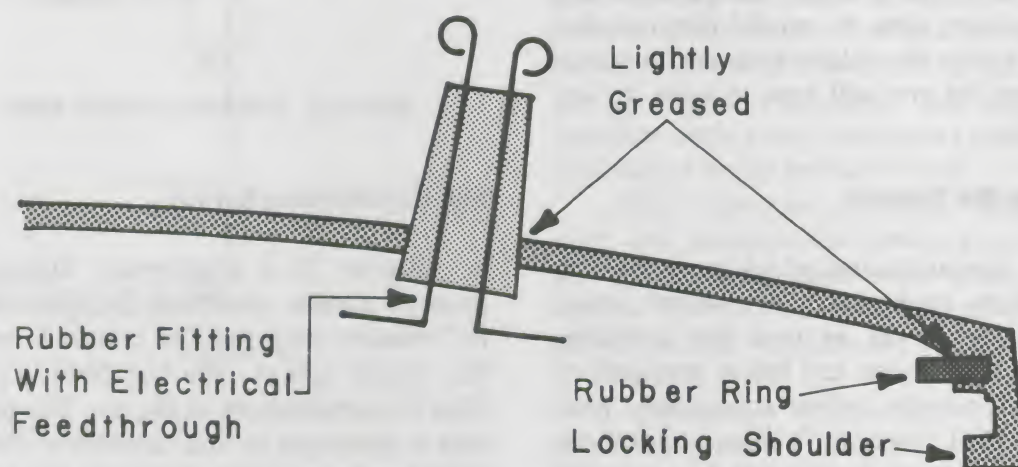


Figure 27.

Assemble the Apparatus

You must assemble the pressure cooker so that it is an airtight container. To get a good pressure seal, remove the gasket and the fitting for the electrical leads. Make sure they are uniformly and *lightly* greased with vacuum grease, then replace them securely. Check that the pressure gauge fittings are tightly screwed in. (See Figure 27.)

When you have completed these preliminary checks, close the pressure cooker carefully, being sure the cover is locked in place. Now try some simple experiments to get a feeling for the parameter of pressure.

SOME SIMPLE TESTS

Test Your Lung Power

First, use the gauge on the pressure cooker to test your lung power. Place a rubber hose on the pressure release hole. Blow in and see how much pressure you can produce.

CAUTION: *This is only a rough test so do not try to burst your lungs.*

Inhale and see what vacuum you can produce, but take it easy.

Are your lungs more effective in producing vacuum or pressure? Record your values.

Lung Pressure _____

Lung Vacuum _____

Test Other Things (Optional)

Using the pressure release hole as an access to the pressure gauge, test the vacuum produced by some other common vacuum devices. For example, an aspirator, a vacuum cleaner, etc. Do you know the principles upon which these devices work?

CAUTION: *Do not test for pressures over atmospheric pressure unless you are sure they are less than 15 lb/in². As you will see later, the forces on the lid become tremendous and could be potentially dangerous!*

Use the Squeeze Bulb

Connect the squeeze bulb to the pressure cooker. How much pressure can be built up? Pay particular attention to the way the bulb feels; is there any evidence that pressure and force are related?

Every time you completely squeeze the bulb you are forcing in approximately the same number of molecules ΔN . How much does the pressure change (ΔP) for each squeeze? Since V and T are fixed, what does this say about the relation between N and P ?

Turn the bulb end-for-end and connect it backwards. Can a vacuum be produced? How much? Why is there a definite limit to the vacuum that can be drawn this way?

Pressure _____

Vacuum _____

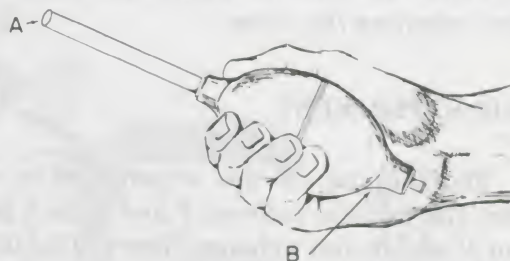


Figure 28. More molecules are forced in at Point A. Increased pressure occurs at point B.

Test for Leaks

The leak test is a modern version of an old procedure used for checking automobile innertubes. Dunking an inflated innertube in a tub of water and watching for bubbles is a very sensitive test for leaks. You can use the

same trick here. Using the rubber bulb, pump the chamber up to a pressure of about 5-10 lb/in². Apply soapy water (or saliva) to all possible places where the container could leak. If you see any growing bubbles, try to eliminate the leak. If it is at a threaded joint, tighten the joint. If the leak is around the electrical feed through, apply more vacuum grease. If there are leaks on the main cover seal, be sure that the gasket is properly seated and coated with a uniform, but not too thick, layer of vacuum grease.

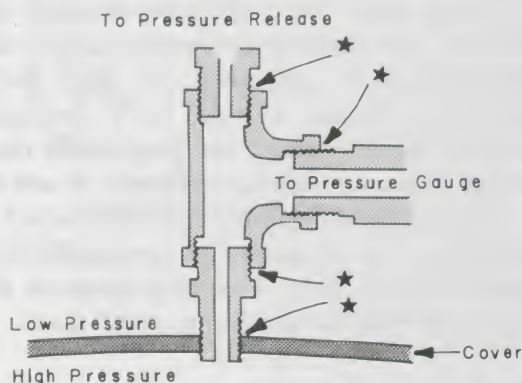


Figure 29. Apply soapy water to starred areas.

CAUTION: Be sure to release the pressure before removing the cover!

YOUR EXPERIMENT

The purpose of this experiment is to obtain the relation between P and T for a gas when V and N don't change. You will do this at chamber pressures below atmospheric pressure. If the inside pressure is less than that outside, the force of the atmosphere will be pushing down on the cover. It will be pressing on the rubber gasket and helping to make a good airtight seal.

If the experiment were performed at pressures in the chamber higher than atmospheric pressure, the gasket would probably still seal (as your leak test showed). However, in general it is best to have atmospheric pressure working with you rather than against you.

Prepare a Data Table

As usual, you will need a table in which you may record your data. Make a table similar to that shown below in the space provided on the data page. In the column for "Notes" be sure to record any actions you took in the procedure (such as adding a fan).

Notes	$R(\Omega)$	$T(^{\circ}\text{C})$	$P(\frac{\text{in}}{\text{Hg}})$		

Calibrate the Thermistor

Check to be sure that the thermistor is operating properly. Zero the ohmmeter and check room temperature and maybe one other point against your calibration scale. Readjust your calibration scale if necessary. An additional scale is provided on the data page.

Perform the Experiment

1. Place the pressure cooker on the hot plate and start heating it. Leave the pressure release off so that the hot gas can escape. Continue heating until the thermistor registers a temperature of about 160°C.

CAUTION: Do not exceed this temperature or the solder in the electrical connections of the thermistor will melt.

2. Remove the cooker from the hot plate when the temperature reaches 160°C and set it on a heat-resistant surface.

CAUTION: 160°C is very hot.

Initially the bottom is the hottest surface and you must wait until the cooker body and the gas inside reach the same temperature. How do you know when this point is

reached? You can't be sure exactly, but a good indication is when the thermistor resistance stops changing rapidly. This should take only a minute or two.

3. *Seal off the chamber*, when the thermistor resistance stops changing, by replacing the pressure release. Take an initial reading of pressure and thermistor resistance. (The pressure gauge should be zero, because the air inside the pressure cooker is at atmospheric pressure immediately after sealing it.)

4. *Continue taking readings* of resistance and pressure as the chamber cools. **NOTE:** Pressure gauges often have a tendency to stick. Before each pressure reading tap the gauge lightly a couple of times. Take readings at each "half-inch" change of pressure.

5. *The cooling process will go slower and slower as the temperature falls.* Do you know why? It can be speeded up by using a

fan to increase the rate of heat losses. **NOTE:** Be sure to stop the fan somewhat before the gauge pressure reaches the pressure you want to read so that all parts of the system have time to reach the same temperature.

6. **OPTIONAL:** Once the cooker has cooled to room temperature, you may want to take additional data below room temperature. This can be done by placing a wet cloth on the cooker with a fan blowing on it (evaporational cooling), placing the cooker in cold water, or putting it outside on a cold day, etc.

Some Final Data

For later calculations you will need data on the *ambient* pressure and temperature, that is, the pressure and temperature of the air surrounding the experiment. Find the values and record them on the data page.

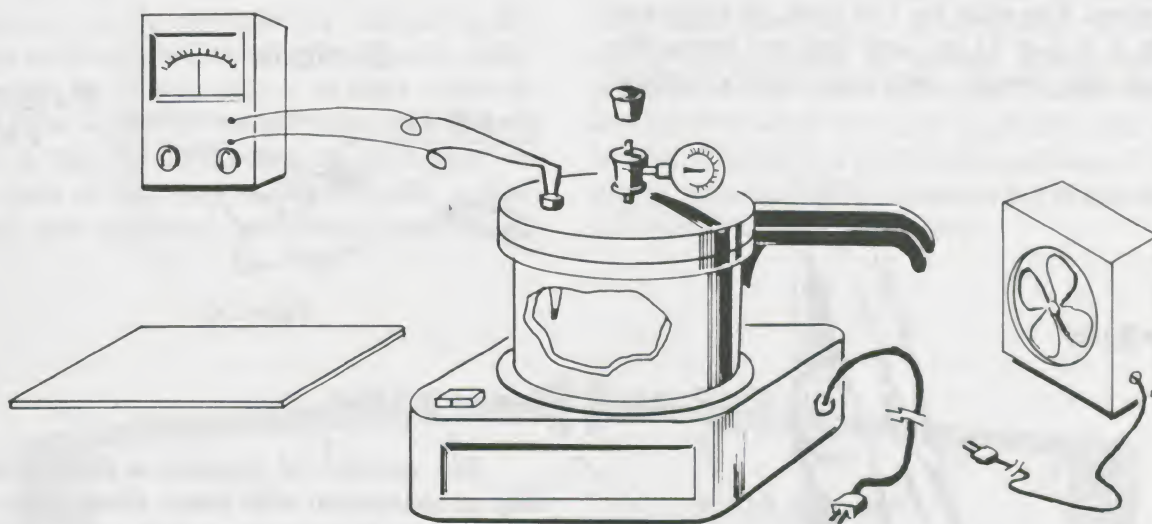


Figure 30.

PRESSURE AND FORCE

Before you begin to analyze your data the parameter of "pressure" will be discussed so that you will have a good idea of what is going on in the pressure cooker. The most important relation is that between pressure and force. They are not the same and this distinction is critical in the pressure cooker and in many other devices in which fluid pressures are involved. Using the force-pressure relation properly has given great power to man. But lack of understanding has led to disastrous accidents.

How Are Force and Pressure Related?

As an example of how pressure and force are related, try pushing on the wall with your hand. Suppose you can exert a push on the wall of about 25 lb. (You might check this value by putting a bathroom scale against the wall and pushing on it.) This is a *force* of 25 lb. The direction of the force is perpendicular to the wall.

Now assume that the palm of your hand is about 3 in wide by 7 in long, or an area of $3 \text{ in} \times 7 \text{ in} = 21 \text{ in}^2$, and that you spread the force out evenly over your hand's surface.

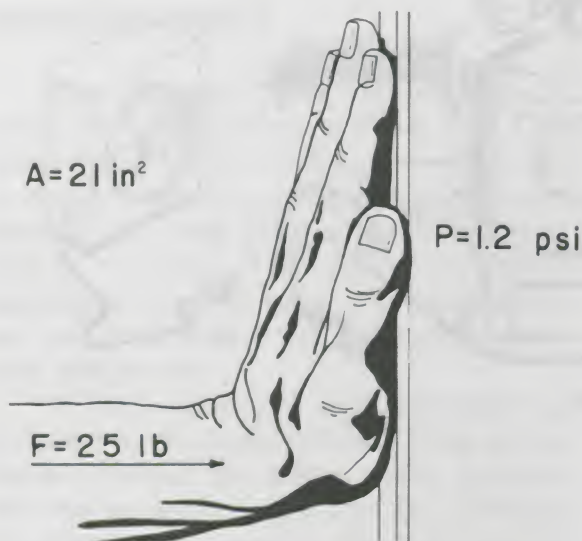


Figure 31.

The 25-lb force is therefore spread over an area of 21 in^2 . The force exerted on *each* square inch of wall is only $25 \text{ lb}/21 \text{ in}^2 = 1.2 \text{ lb/in}^2$. This quantity is called the *pressure* on the wall, the number of pounds of force exerted on each square inch of surface.

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}}$$

Now suppose that instead of pushing with your palm against the wall you push with only one finger. The end of your finger is roughly $\frac{1}{2}$ inch square or an area of $\frac{1}{2} \text{ in} \times \frac{1}{2} \text{ in} = \frac{1}{4} \text{ in}^2$. If your arm still exerts a force of 25 lb, the pressure on the wall is:

$$\begin{aligned} P &= \frac{25 \text{ lb}}{\frac{1}{4} \text{ in}^2} = 100 \text{ lb/in}^2 \\ &= 100 \text{ psi} \end{aligned}$$

Thus by exerting the same force you can produce a pressure ranging between 1 and 100 psi.

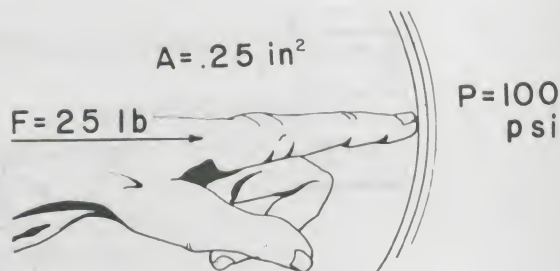


Figure 32.

Pressure in Fluids

The concept of pressure is more often used in connection with fluids, either gases or liquids, than in connection with solids. When a gas is *compressed* (forced to occupy a smaller volume) it is "under pressure." This pressure exists everywhere in the gas. For example, when you squeeze the bulb you exert a force on it and the gas inside is compressed, increasing its pressure.

Pressure is a measure of how hard a fluid pushes (the force) on the surfaces that it contacts (as well as how hard one part of a fluid pushes on the part next to it). The forces that the fluid exerts are called *pressure forces*.

Since forces have both magnitude and direction, we must indicate the direction of these forces. The direction is determined by the fact that a *pressure force always acts at right angles to the surface that the fluid touches*, no matter what the orientation of the surface.

Forces in the Pressure Cooker

The surface of particular interest in the pressure cooker is the cover. It is necessary to know the force on the cover to determine how strong the cover latch must be. As seen in the diagram below, the cover is dome-shaped and the forces on it are not all acting vertically to push it off. Some of the forces act in directions which are up and to the right or left.

The total vertical force on the lid, however, can be calculated by calculating the force on the lid as if it were flat. That is, a flat area can be chosen that is at right angles to the force direction we are concerned about.

A flat lid would have an area equal to the area of the top of the pressure cooker body, and the force on it would be equal to

the product of that area times the pressure. For example, for a top diameter of 8.0 in, the area would be:

$$A = \pi \frac{d^2}{4} \approx 50 \text{ in}^2$$

If the pressure in the cooker were 15 lb/in², the total force on the lid would be:

$$F = P \times A = 15 \times 50 = 750 \text{ lb}$$

PRESSURE UNITS

There are several units for measuring pressure. The chart in Figure 34 shows some of them and how they are related. There are three broad methods for specifying pressure, as follows.

Atmospheres

Sometimes, particularly when specifying very high pressures, it is convenient to use simply the normal or average atmospheric pressure as the unit. This unit is called the *atmosphere* (atm). A nearly equivalent unit is the *bar*. The bar is a convenient unit since it is nearly equal to one atmosphere yet is exactly 10⁵ N/m² in the metric system.

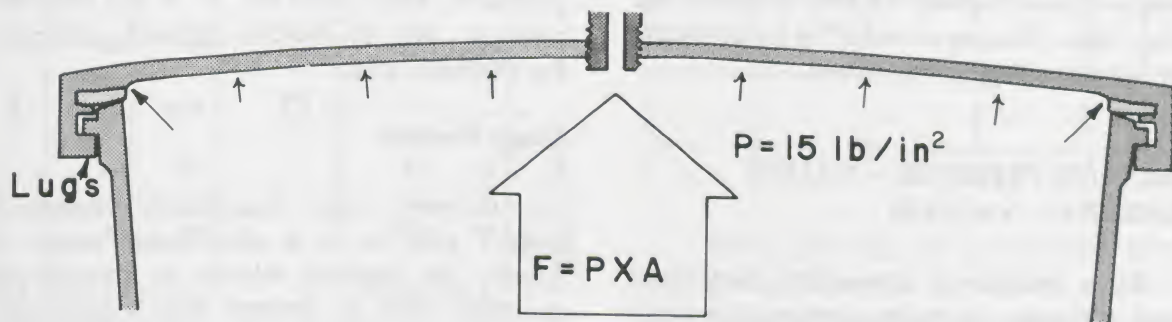


Figure 33. The force attempting to blow off the lid is simply the cross sectional area of the top times the pressure in the chamber. This force must be safely held by the lugs on the top and body of the pressure cooker.

Force Per Unit Area

Another unit is in terms of force per unit area, as discussed on the previous pages. In the English system this is *pounds per square inch*, lb/in^2 (or psi) and in the metric system, *newtons per square meter* (N/m^2) or *dynes per square centimeter* (dyn/cm^2). The newton per square meter is now called the pascal (Pa), and it is the SI unit of pressure. As you can see from Figure 34, one atmosphere is about 14.7 psi, $1.013 \times 10^5 \text{ N/m}^2$ or $1.013 \times 10^6 \text{ dyn/cm}^2$.

Liquid Columns

In scientific applications pressures are measured in terms of the height of the column of liquid that the pressure will support. A mercury barometer is made by filling a long glass tube with mercury and inverting it into a dish of mercury. Then, in the tube above the mercury there is a near-vacuum. At the bottom of the tube air pressure acts to support a column of mercury whose height is proportional to the pressure. A pressure of one atmosphere will support a mercury column 29.92 in or 760 mm high. Therefore, pressures are often expressed in inches or millimeters of mercury (in Hg or mm Hg). A millimeter of mercury is also referred to as a Torricelli or a Torr. Your vacuum readings in this experiment are expressed in inches of mercury below atmospheric pressure. Note that atmospheric pressure will support a column of water about 34 feet or about 407 inches high. "Inches of water" is a convenient unit for measuring low pressures.

ABSOLUTE PRESSURE – GAUGE PRESSURE – VACUUM

Even though our atmosphere is not in a closed container, it exerts a pressure on every surface in the atmosphere.

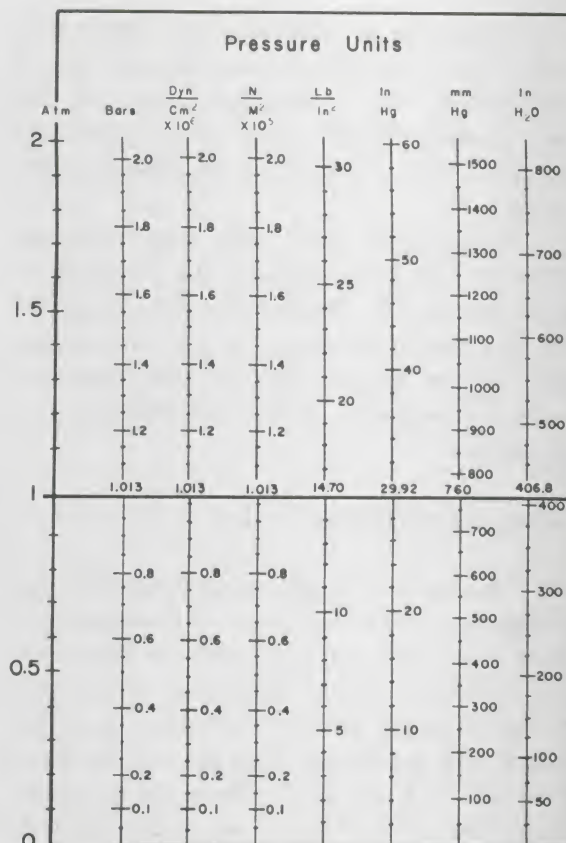


Figure 34.

Absolute Pressure

There are two ways of stating pressure. If it is measured starting from zero pressure, then it is called *absolute pressure*.

When normal atmospheric pressure is 14.7 psi, this is an absolute pressure. The pressures shown in Figure 34 are absolute pressures. Very often an "a" is put after the pressure unit to indicate absolute pressure, for example, psia.

Gauge Pressure

However, since atmospheric pressure is always with us, it is often more useful to specify the pressure relative to atmospheric pressure. That is, pretend that atmospheric pressure is zero (as you saw on your pressure

gauge) and specify the pressure relative to that. The pressure measured relative to one atmosphere is called *gauge pressure*. When tires are inflated to 30 lb/in², that is 30 psi gauge pressure and about 45 psi absolute. The letter "g" is often put after the unit to indicate gauge pressure; for example, psig. To get the absolute pressure in the tires add the atmospheric pressure.

$$P_{abs} = P_{atmos} + P_{gauge}$$

Vacuum

Gauge pressure below atmospheric pressure is called *vacuum*, since one has to evacuate a region to get a pressure below

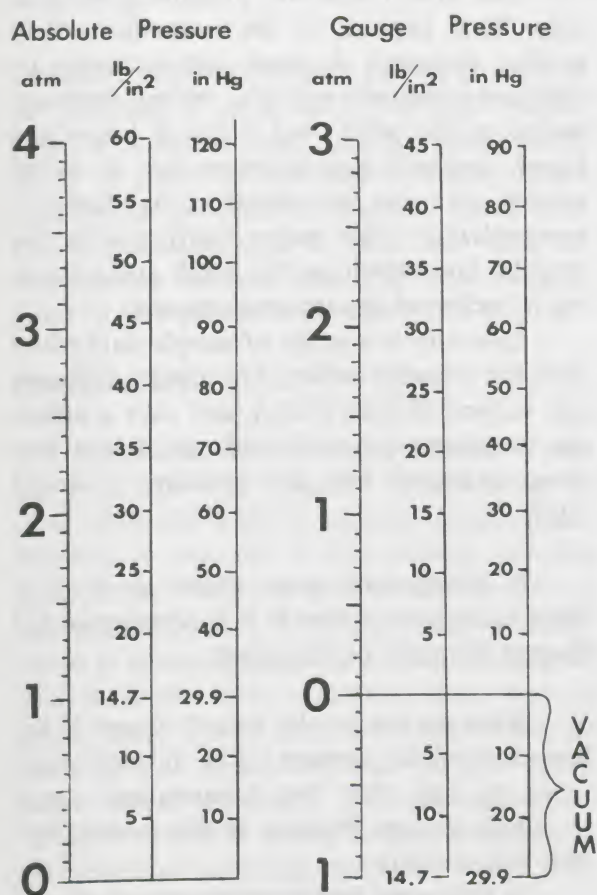


Figure 35.

atmospheric pressure. A perfect vacuum exists when there is zero absolute pressure. The units specifying vacuum on the gauge are the reverse of the units from zero to one atmosphere. That is, a perfect vacuum (gauge pressure) is 14.7 psi, 29.92 in Hg, or 760 mm Hg, etc.

$$P_{abs} = P_{atmos} - P_{gauge}$$

ANALYZING YOUR DATA

As usual, after collecting data from an experiment the results must be analyzed and displayed so that their meaning is clear. In this case, we want to know the mathematical relation between pressure and temperature. A graph of these two will illustrate the relation nicely. Follow the procedure below to obtain your graph.

1. *Complete the data table.* The first step is to convert the data into pressures and temperatures of convenient units. Using your thermistor calibration scale, convert your resistance values into temperatures.

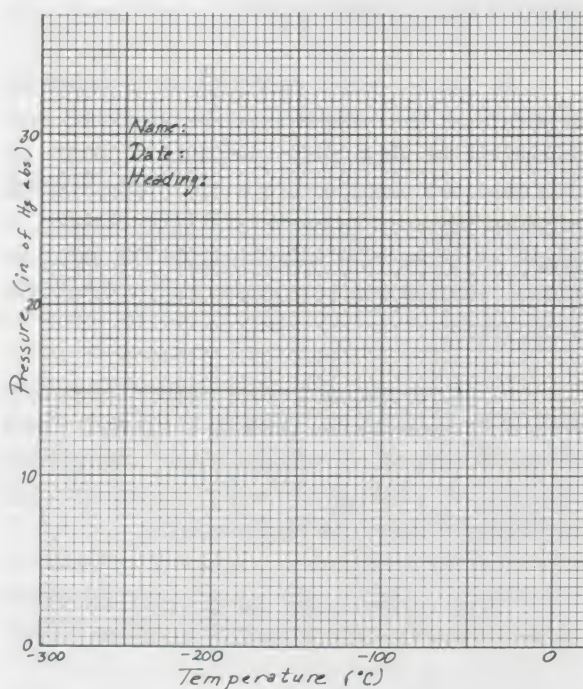
Next, convert the gauge pressure readings of vacuum into absolute pressure values.

$$P_{abs} = P_{atmos} - P_{gauge}$$

Notes	R (Ω)	T (°C)	Absolute	
			Gauge P (in Hg)	P

Using the value of atmospheric pressure determined from the barometer, convert the gauge pressure to absolute pressure. Express the results in inches of mercury absolute.

2. *Prepare the graph paper.* In setting up the graph of P versus T , let T be on the abscissa (x-axis) and P on the ordinate (y-axis). Start the pressure axis from 0, but start the temperature axis considerably below 0, say -300°C . The reason for this will be explained later. Portions of a typical graph are shown as an example.



Sample student graph.

3. *Plot the data.* Now plot the P – T data points on the graph. You will find that they occupy only a small portion of the graph.

4. *Draw the graph.* Your data points should fall pretty nearly on a straight line. Draw a straight line through the points. In general this means that the number of points that are above the line equals the number that are below.

What Does the Graph Mean?

Since the graph of pressure against temperature is a straight line, the relation between absolute pressure and Celsius temperature is “linear.” This is not the same as saying that these two quantities are proportional. If they were proportional to one another, then the pressure would be zero at 0°C ; this is obviously not true here. Also when quantities are proportional, if you double one then the other one is doubled also. Look at how the pressure changes from say 50°C to 100°C ; it certainly does not double. To answer the questions raised above let us now ask the following question.

At $P = 0$, What Is T ?

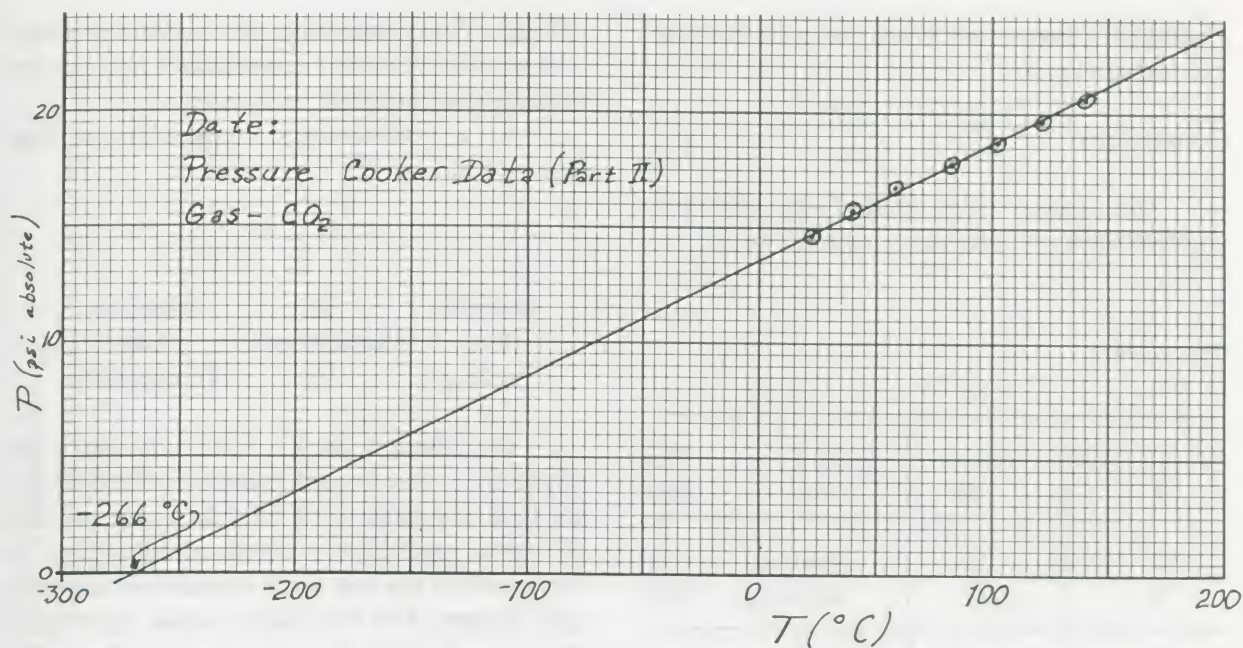
The lowest absolute pressure possible is zero. What happens to the temperature then at that pressure? A good answer cannot be obtained without actually taking measurements to see what does occur at lower and lower pressures and temperatures. A useful general idea can be arrived at by doing an *extrapolation*. This means starting with the straight line drawn on the graph and extending it backward toward zero pressure.

Opposite is a graph of sample data taken with the pressure cooker, but using a different gas, carbon dioxide (CO_2), and over a different pressure region. On this graph the line when extended hits zero pressure at about -266°C .

5. *Extrapolate your graph to $P = 0$.* What temperature does $P = 0$ correspond to? Record the value on the graph.

What do the results mean? If zero is the lowest possible pressure, then it may make sense to say that the temperature corresponding to zero pressure is the lowest possible temperature.

Is this same temperature arrived at only in this particular set of circumstances? For



Sample student graph.

example, does the number change if a different amount of air is used? When the experiment is repeated many, many times with all kinds of gases, and different amounts of gas, the results are always about the same. With careful measurements it turns out that the temperature reached when the line is extrapolated to zero pressure is *always* -273°C .

Absolute Zero

Since this temperature, -273°C , crops up over and over again, it makes sense to think that this really is a special temperature. Perhaps it actually is the lowest possible temperature. The evidence in this module is not positive proof. For one thing, extrapolation is always dangerous, since the results of measurements are extended into regions where those results may not apply. Also, all gases become liquid and most become solids long before reaching a temperature of -273°C . And it is hardly correct to speak of gas pressure becoming zero when the substances are in fact no longer gases.

In spite of these difficulties, other evi-

dence does indicate that -273°C is indeed a special temperature, and the lowest attainable. Laboratory experiments of many different kinds in which the aim is to make the temperature as low as possible show that the lower limit is -273°C . (More precisely, -273.15°C .)

SCALES OF TEMPERATURE

This temperature is called *absolute zero* since it is absolutely as low as temperature can get. Using this as the zero temperature of a new temperature scale, and choosing the same size degrees as $^{\circ}\text{C}$, we define a new temperature scale called the *kelvin* scale, for which the units are kelvins (K). The kelvin scale is called the *absolute temperature scale*. It is much like the absolute pressure scale which has its zero at the lowest possible absolute pressure.

When similar measurements are made using the Fahrenheit scale of temperature, absolute zero is found to be approximately -460°F . When this point is used as the zero and degrees which are the same size as

Fahrenheit degrees are used, the scale is called the *Rankine scale*.

Conversions

The simple rules below will help you convert from one scale to another:

To convert from	to		
°C	K	Add	273
°F	°R	Add	460
K	°C	Subtract	273
°R	°F	Subtract	460
K	°R	Multiply by	9/5
°R	K	Multiply by	5/9

KELVIN TEMPERATURE SIMPLIFIES THE P - T RELATION

The reason for introducing absolute zero and kelvin temperature is to simplify the analysis of the P - T relation for a gas and thus get us closer to the mathematical expression for the General Gas Law. To see this do the following.

6. *Replot the data in kelvin temperature.* First convert the temperature data from °C to K and then make a new graph of P versus T .

The graph opposite shows sample data plotted as pressure against *kelvin* temperature. Notice that the pressure is now zero when the temperature is zero. Also note that when the temperature is doubled (from say 200 K to 400 K) the pressure doubles (from 10 psi to

20 psi). This means that the *absolute pressure and absolute (kelvin) temperature of a gas are directly proportional*.

As a mathematical expression we can thus write:

$$P \propto T$$

Absolute Gas Pressure is Proportional to Absolute Gas Temperature

This then is the P - T relation for a gas when the volume and number of molecules are held constant. This relation holds true for all gases, regardless of their composition. In this case the gas was air, a mixture of nitrogen and oxygen, but the results would have been the same for the two gases separately or for any other gas chosen: helium, carbon dioxide, steam, etc.

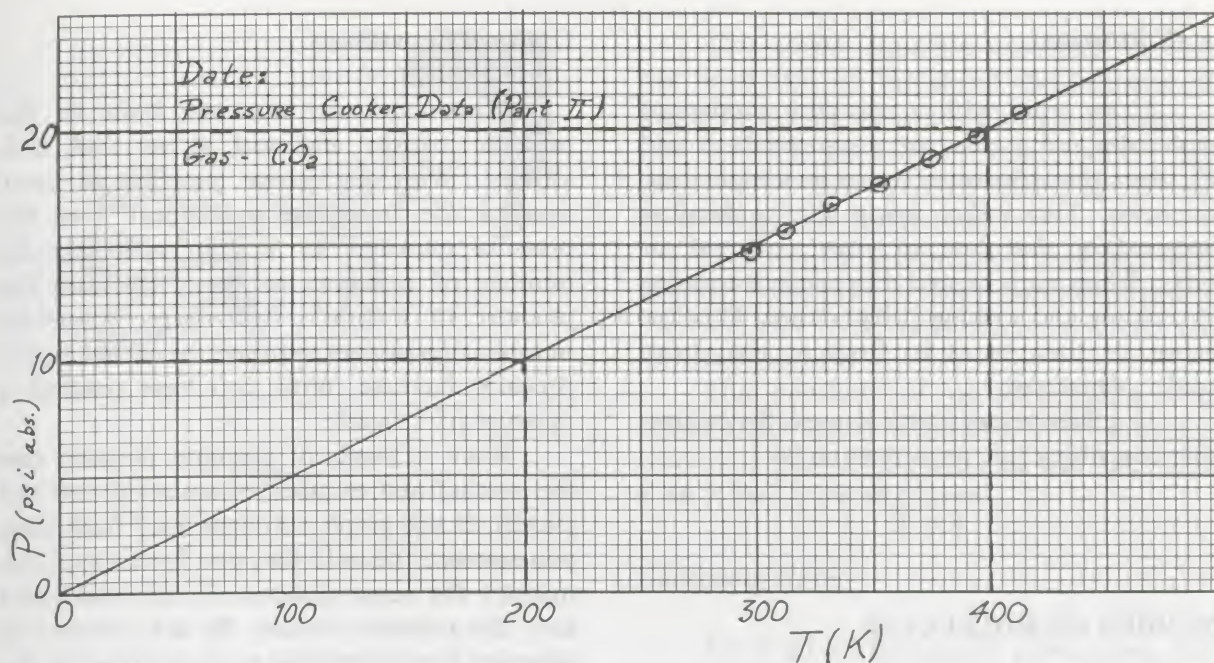
Optional Experiment

To verify the above statement, redo this experiment using another gas. (For example, you could fill the pressure cooker with carbon dioxide by putting a small piece of dry ice on the bottom of the cooker, closing it and allowing the carbon dioxide to push the air out of the hole at the top.) Extrapolate the data to zero pressure and see if the value of absolute zero is the same.

OTHER P , V , T , N RELATIONS FROM YOUR EXPERIENCE

The pressure cooker experiment has thus given the P - T relation for a gas. But there are two other parameters, the volume, V , and the number of molecules, N . Thus there are more relations to determine before a complete expression for the General Gas Law can be obtained.

Many of these relations can be drawn from your own experience. Some of these will be discussed to lead to relations that would



Sample student graph.

result if experiments were performed. By pulling together these relations we will then be able to suggest a form for the General Gas Law which will summarize them all.

VOLUME

Volume is a parameter with which you should now be quite familiar. It is measured in cubic measure; cubic inches (in^3), cubic centimeters (cm^3), etc. However, in the case of the pressure cooker it is specified in quarts, a common volume measurement for liquids. One quart is about equal to one liter which is exactly 1000 cm^3 . This is a useful rough conversion between the English and metric systems of volume units.

V - P Relation

The volume of a gas is related to its pressure. A simple way to convince yourself of this is to recall the bulb used to pump up the pressure cooker.

If the air release hole is closed (thus fixing the number of molecules) and the bulb is squeezed, the volume of air in the bulb decreases but the force exerted gets larger. The fact that you must squeeze harder indicates that the air pressure is increasing.

If P is the *absolute* gas pressure, then P and the volume V are related very nearly by:

$$V \propto \frac{1}{P}$$

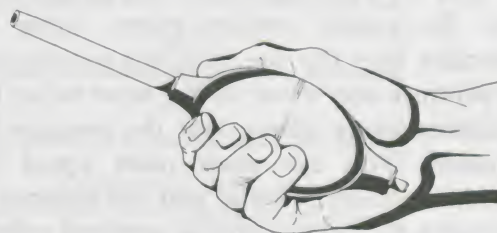


Figure 36.

V-T Relation

If we work with a constant number of molecules and a constant pressure (fix N and P), then the volume increases as temperature increases. This effect leads to the familiar observation that hot air rises and cold air sinks. When air is heated it expands increasing its volume and making it less dense. This less dense air then tends to float or rise above colder, denser air.

If *kelvin* temperature is used the expression describing this phenomenon is:

$$V \propto T$$

NUMBER OF MOLECULES

It was stated earlier that the General Gas Law is concerned with N , the number of molecules of the sample of gas examined. It is not easy to determine N , but it can be computed if the mass of the gas and some other facts about it are known. In this module, N will always be kept fixed and it does not need to be known. The interesting thing, as you will see, is that for *any* gas the General Gas Law has the same form. That is, samples of two different gases with different weights will behave identically if they contain the same number of molecules.

N-P Relation

The N - P relation can be illustrated by the tires on your car. When you inflate your tires, the service station pump forces air molecules into the tire. The tire volume and temperature stay close to the same value, but a pressure gauge shows that the pressure has increased. You can learn more about the relation between pressure and the number of molecules by doing a simple optional experiment using the pressure cooker.

Optional Experiment

Re-connect the squeeze bulb to the pressure cooker and seal it so that it is airtight. With the gauge pressure at zero, squeeze the bulb flat and repeat until the pressure increases to 1 lb/in^2 . Record the number of squeezes necessary to raise the pressure to 1 lb/in^2 . Repeat, recording the number of squeezes required for each 1 lb/in^2 pressure increase, until you have reached a pressure of 5 lb/in^2 .

Make a graph of absolute pressure (on the y -axis) and number of squeezes (on the x -axis). Is this graph a straight line? Each time you squeeze the bulb flat, you force (approximately) the same number of molecules (ΔN) into the pressure cooker. So the number of squeezes is proportional to the increase in the number of molecules. If you knew the value of ΔN , you could use your data to make a plot of P versus N . The only difference would be the scale on the x -axis. The shape of the graph would be the same, a straight line.

If absolute pressure is used, and volume and temperature are constant, then the N - P relation is

$$P \propto N$$

N-V Relation

The relation between N and V can be seen by considering a paper bag. When you blow up a paper bag you simply put more molecules into the bag. The temperature of the bag does not rise much and the pressure inside does not increase much (T and P fixed), the bag just opens up more to increase its volume.

The description of this is

$$V \propto N$$



Figure 37.

THE GENERAL GAS LAW

All of the relations discussed may be summarized by the proportion:

$$PV \propto NT$$

If a constant of proportionality is defined as k , the mathematical expression of the General Gas Law is:

$$PV = kNT$$

This single equation expresses all that has been said so far about the behavior of gases. It can be used to calculate changes in one of the parameters when others are changed. Convince yourself that it agrees with all of the earlier discussions.

It must be remembered however, that *absolute values of pressure and temperature must be used* in all calculations involving the General Gas Law.

The constant of proportionality k is called *Boltzmann's Constant*. It is a fundamental physical constant and has the value 1.38×10^{-23} J/K in SI units.

Consistent Units

As in all mathematical expressions, the same type of units must be used for all the parameters. For example, if one quantity is in SI units, they all must be SI. Table VI shows correct units for both SI and English systems.

Now that we have an expression for the behavior of a gas let's see how it can be used. Following are two calculations that demonstrate the types of questions that the General Gas Law can help answer. In these examples it is not necessary to use the whole gas law expression, but simply to recognize which parameters change and which are fixed, then to apply the proper proportionality relation.

Table VI. Units for the General Gas Law

	SI	English
P	N/m ²	lb/in ²
V	m ³	in ³
T	K	°R
N	Number of molecules	Number of molecules
k	1.38×10^{-23} J/K	6.79×10^{-23} in lb/°R

Example: How Much Does Tire Pressure Increase as Tires Heat Up?

An automobile tire is inflated to 30 psi (gauge) when the temperature is 60°F. After some high speed driving the tire temperature rises to 150°F. What is the pressure of the air in the tires now?

From the statement of the question and experience we can deduce the following:

Initial Tire Conditions:

$$P_i = 30 \text{ psi (gauge)}$$

$$T_i = 60^\circ\text{F}$$

Final Tire Conditions:

$$P_f = \text{to be determined}$$

$$T_f = 150^\circ\text{F}$$

We can assume that the tire does not leak so that:

$$N_i = N_f = N \text{ (fixed)}$$

Also assuming that the tire doesn't increase significantly in size:

$$V_i = V_f = V \text{ (fixed)}$$

Writing the General Gas Law for these two conditions:

$$P_f V = NkT_f$$

$$P_i V = NkT_i$$

Dividing one by the other gives the proportionality:

$$\frac{P_f}{P_i} = \frac{T_f}{T_i}$$

Since the General Gas Law requires absolute pressure and absolute (kelvin) temperature, first convert the values of P_i , T_i and T_f to these:

$$P_i = 30 \text{ psi (gauge)}$$

$$= 45 \text{ psi (absolute)}$$

$$T_i = 60^\circ\text{F} = 16^\circ\text{C} = 289 \text{ K}$$

$$T_f = 150^\circ\text{F} = 65^\circ\text{C} = 338 \text{ K}$$

Substituting these values into the equation gives

$$\frac{P_f}{45 \text{ psi}} = \frac{338 \text{ K}}{289 \text{ K}}$$

so

$$\begin{aligned} P_f &= \frac{338}{289} \times 45 \text{ psi} \\ &= 53 \text{ psi (absolute)} \end{aligned}$$

or

$$P_f = 38 \text{ psi (gauge)}$$

CHECKING TIRE PRESSURE*

Check tire pressure while the tires are "cold." This should be done after the car has been parked at least one hour and before driving more than three miles. Operation at high speeds will heat the tires enough to increase tire pressure considerably. An eight-pound increase over "cold" pressure is not unusual. Therefore one should not bleed air from a "hot" tire because the pressure is higher than normal.

*Instructions from an automobile owner's manual.

Example: How High Does the Pressure Get in an Engine Cylinder?

The compression ratio of a certain gasoline engine is 9.5:1. That is, the volume of gas in the cylinder when the piston is at the bottom of its stroke is 9.5 times the volume at the top of its stroke. If a charge of fuel-air mixture is drawn in at the bottom of the stroke at 2.0 psi vacuum, what is the pressure in the piston at the top of the stroke? (Assume that the temperature of the mixture does not change.)

From the statement of the question we can write down that:

$$P_i = 2.0 \text{ psi vacuum}$$

$$V_i = \text{not known but } 9.5 V_f$$

$$P_f = \text{to be determined}$$

$$V_f = \text{not known}$$

We are assuming

$$T_i = T_f = T \text{ fixed}$$

$$N_i = N_f = N \text{ fixed}$$

Writing the General Gas Law for these two conditions gives:

$$P_i V_i = NkT$$

$$P_f V_f = NkT$$

Substituting for V_i and dividing one equation by the other gives

$$\frac{P_f}{P_i} \frac{V_f}{(9.5 V_f)} = \frac{NkT}{NkT}$$

or the proportionality:

$$\frac{P_f}{9.5 P_i} = 1$$

or

$$P_f = 9.5 P_i$$

Recalling that the General Gas Law requires absolute values:

$$P_i = 2 \text{ psi vacuum}$$

$$= 12.7 \text{ psi abs}$$

Substituting this into the equation gives:

$$P_f = 9.5 \times 12.7 \text{ psi abs}$$

$$= 121 \text{ psi abs}$$

or

$$P_f = 106 \text{ psi gauge}$$

USING A COMPRESSION GAUGE*

A very important engine testing gauge is the compression tester. It measures the pressure within the cylinders in pounds per square inch. The numerical reading is not so important as the variation between cylinders. The cylinder pressures should not vary over 15 psi; otherwise, as this will cause uneven idling and loss of power, the engine cannot be tuned properly. To use the gauge, remove all the spark plugs and insert the rubber tip into a spark plug hole. With the throttle held wide open, crank the engine over about 6 times, recording the gauge reading. Do this at each cylinder in turn and compare the results. Generally, modern high-compression engines should have a reading close to 175 psi.

*From an auto repair manual.

This answer does not correspond too closely to the information from the auto repair manual. This is mainly because the assumption that the temperature remains the same during the compression stroke is not a

valid one. Can you think of any evidence you have seen that the temperature actually does change when a gas is suddenly compressed or expanded?

HOW TO USE THE TABLE

If you have a unit in column A and you want a unit in row B, multiply by the factor shown at the intersection of column A and row B.

FOR EXAMPLE: If you have lb/in^2 and you want mm Hg, multiply by:

$$51.7 \frac{\text{mm Hg}}{\text{lb/in}^2}$$

$$A (\text{lb/in}^2) \times 51.7 \frac{\text{mm Hg}}{\text{lb/in}^2} = B (\text{mm Hg})$$

Table VII.

PRESSURE UNITS AND CONVERSION FACTORS

A \ B	atm	bar	dyn/cm ²	N/m ²	lb/in ²	in Hg	mm Hg (Torr)	in H ₂ O
atm	1	1.013	1.01×10^6	1.013	14.7	29.9	760	407
bar	.987	1	10^6	.987	14.5	29.5	750	402
dyn/cm ²	9.87×10^{-7}	10^{-6}	1	.100	1.45×10^{-5}	2.95×10^{-5}	7.50×10^{-4}	4.02×10^{-4}
N/in ²	.987	1.013	10	1	1.45×10^{-4}	2.95×10^{-4}	7.50×10^{-3}	4.02×10^{-3}
lb/in ²	.0680	0.0689	6.89×10^4	6.89×10^3	1	2.04	51.7	27.7
in Hg	.0334	.0338	3.39×10^4	3.38×10^3	.491	1	25.4	13.6
mm Hg (Torr)	1.32×10^{-3}	1.33×10^{-3}	1330	133	1.94×10^{-2}	.393	1	.535
in H ₂ O	2.46×10^{-3}	2.49×10^{-3}	2490	249	.0361	.0736	1.87	1

REVIEW: Summary of Section B

Section B of this module is concerned with the behavior of gases. The condition or *state* of a gas is described by listing four quantities called *variables* or *parameters*: *absolute pressure*, P ; *volume*, V ; *number of molecules*, N ; and *absolute temperature*, T . Changes in the state of a gas are described by the *General Gas Law*.

In Experiment B-1, a sealed pressure cooker (N and V held constant) was used to measure changes in gas pressure as the temperature changed.

Pressure is defined as force per unit area: $P = F/A$. When pressure is acting over an area, the total force is given by $F = PA$. *Absolute pressure* means pressure measured relative to zero pressure. *Atmospheric pressure* at sea level is about 14.7 lb/in^2 absolute. *Gauge pressure* is the pressure measured *above* atmospheric pressure. *Vacuum* is the amount of pressure *below* atmospheric pressure.

The experiment showed that pressure is proportional to temperature. *Extrapolation* of the P - T graph indicates that the pressure of a gas would become zero at -273°C . Other evidence makes us regard this as the lowest possible temperature, *absolute zero*. There are two *absolute temperature scales*: *Kelvin* and *Rankine*.

The results of the experiment, plus other observations about the behavior of gases, can all be summed up in one equation, the *General Gas Law*:

$$PV = kNT$$

The constant k is called *Boltzmann's Constant*.

PROBLEMS

1. Scuba tanks are generally filled with compressed air at 2200 psi absolute. A tank was filled to this pressure at a temperature of 20°C (68°F). Later this tank was left for

several hours in the trunk of an automobile, where the temperature reached 66°C (150°F). The tank is rated at 2900 psi bursting pressure. Do you consider this was a safe thing to do? Explain.

2. An air bubble of 15 cm^3 volume is at the bottom of a lake where the temperature is 4°C and the pressure 4 atm gauge. The bubble rises to the surface where the water temperature is 20°C . Assuming that the air in the bubble has the same temperature as the surrounding water, calculate the volume of the bubble just before it reaches the surface.

3. Oxygen boils at -182.97°C . Express this temperature on the kelvin scale.

4. The normal human body temperature is 98.6°F . Express this on the kelvin scale.

5. The temperature of the sun's surface is about 6000 K. Express this in $^\circ\text{F}$.

6. A certain compound pressure gauge reads 12.5 in Hg vacuum. What is the absolute pressure in units of Hg? Express this pressure in atm. Express this pressure in N/m^2 .

7. The pressure in the ocean increases one atmosphere for every 33 ft of depth. What is the gauge pressure at a depth of 132 ft? The absolute pressure? (Express in psi.)

What would be the total force on a surface of 10 in^2 ?

8. The pressure inside a laboratory autoclave (similar to a pressure cooker) is to be regulated to a maximum value of 30 psig. The regulating weight rests over a tube of area 0.05 in^2 . What should be the weight of the regulating weight?

9. The piston of an air compressor has a cross-section area of 15 in^2 . At one point in

its stroke the total force exerted by the piston is 2500 lb. What is the pressure of the air contained in the cylinder of the compressor?

10. The compression ratio of a gasoline engine is 9.5:1. That is, the volume of gas in the cylinder when the piston is at the bottom of its stroke is 9.5 times the volume at the other end of the stroke.

A certain charge of fuel-air mixture at

the maximum volume has a pressure of 12 lb/in² at a temperature of 70°C. When fully compressed in the cylinder the temperature rises to 300°C.

What is the pressure of the fuel-air mixture when it is fully compressed in the cylinder? (Note that there are mixed English and MKS units here. Is that all right, or must they be converted?)

SECTION C

Phase Diagrams

DESCRIBING SUBSTANCES BY USING GRAPHS

In Section B you found that the behavior of gases could be described by the General Gas Law. This equation is a relation among the four parameters (P , V , N , and T). It can be applied to approximately predict the behavior of any gas when one of the parameters changes.

Can this Gas Law always be applied? If a gas condenses to form a liquid does the equation still apply, or does another one take over? Or is there a bigger, more general equation, say a General Substance Law, which will express the relations between P , V , T , and N over all their possible values?

The answer is no. Substances are much too complicated for such a universal relation. No simple single equation will do for all phases of the substance what the General Gas Law does for the gas phase. Physicists have developed equations which describe many aspects of substance behavior, but in general these equations are complicated and inconvenient.

Therefore another way of describing the behavior of substances is required. This means a way of presenting the experimental data for a substance so that it can be easily used to illustrate the various relationships. As in your experiments, a graph is most helpful.

Phase Diagrams

Graphs which display relationships between the parameters for the various phases of substances are called *phase diagrams*. Since graphs have only two axes, the phase diagram can only display the relation between two of the parameters at a time. Several phase diagrams may be required to completely describe a substance.

Generally, however, one is only interested in certain pairs of relations. The two most common phase diagrams are the P - T (pressure versus temperature) diagram and the P - V (pressure versus volume) diagram. For the pressure cooker, the P - T diagram for water is of most interest.

Figure 38 shows a typical P - T diagram. The lines separate the graph into regions of pressure and temperature for which the substance can exist as a solid, a liquid, or a vapor. Each of these regions defines all of the possible values of P and T for which the substance will be in that phase.

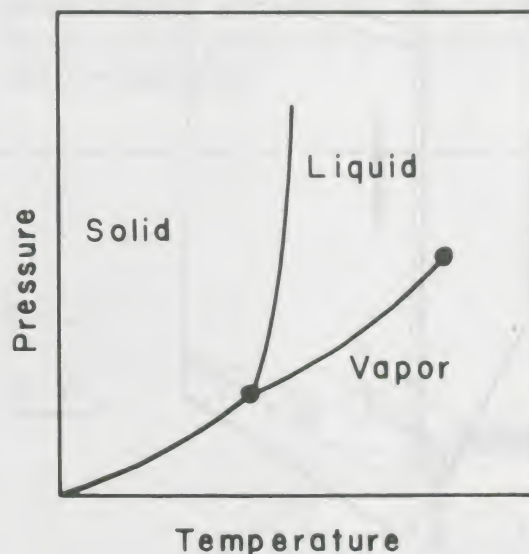


Figure 38.

TECHNOLOGICAL SYSTEMS DESCRIBED BY PHASE DIAGRAMS

Modern technology uses the change in boiling temperature with pressure in many important ways. Figure 39A, B, and C show a few of many possible examples. In each case, the process can be readily explained

by understanding the phase diagram for the substance.

Refrigeration Systems

Most refrigerating systems cool by having a substance evaporate from a liquid to a gas. When a liquid evaporates, a large amount of heat energy is absorbed in its latent heat of vaporization. The substance Freon was specifically developed for such systems. The temperatures and pressures of its phase changes have been designed to make cooking systems compact, safe and efficient.

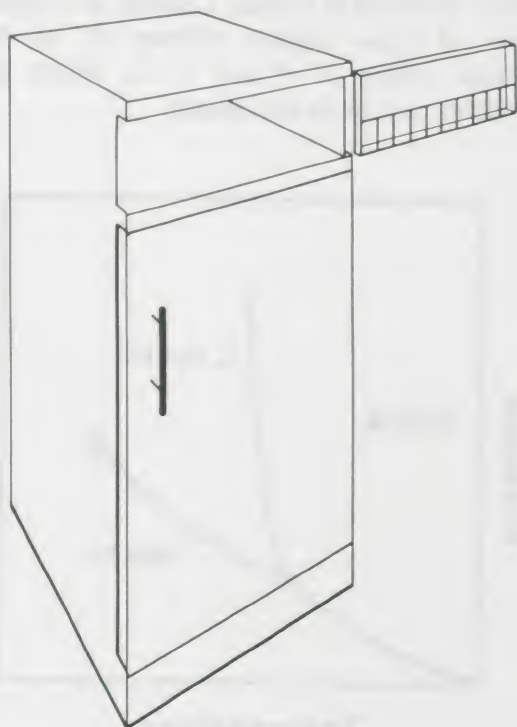


Figure 39A.

Automobile Cooling Systems

Automobile cooling systems are sealed with a cap that regulates the pressure at about 15 psig. With water in the system the temperature can rise to 245°F without boiling. Most manufacturers, however, recommend a mix-

ture of 50% ethylene glycol and water. This has a boiling temperature of 260°F . This higher boiling temperature permits a smaller, more efficient radiator.

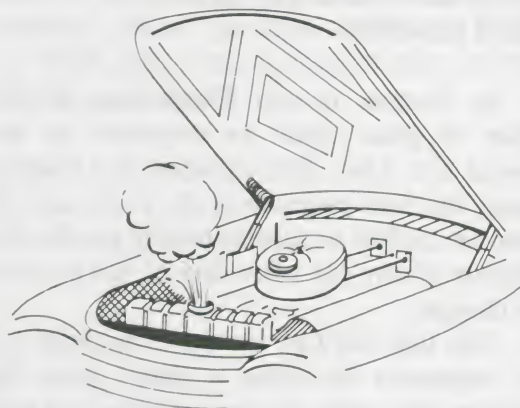


Figure 39B.

"Gas" Storage and Transport

Natural gas and propane used for cooking and heating take up too much space as a gas to be used for fuel for house trailers, campers, torches, etc. The phase diagrams of propane show that it condenses to a liquid at -40°F at 1 atm. But at a pressure of 200 psi it is a liquid for any temperature below 100°F . Thus, "bottled gas" is really a "bottled liquid" that converts to a gas when the pressure is reduced to one atmosphere.

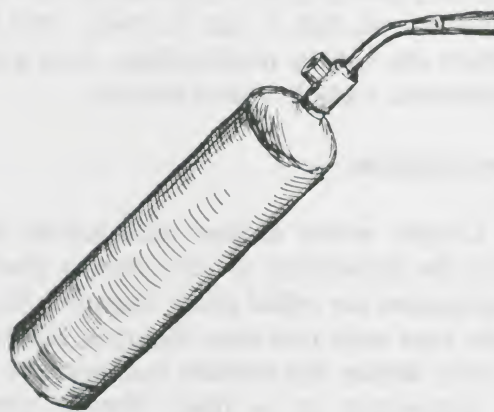


Figure 39C.

YOUR EXPERIMENTS WITH THE PRESSURE COOKER

The Phase Diagram for Water

In this section of the module you will experimentally measure part of the P - T phase diagram for water, using the pressure cooker. You will put some water in the bottom, bring it to a boil and then let the pressure rise until the weight lifts off to regulate the pressure. As the pressure increases you will measure the temperature of the steam with the thermistor, and its pressure with the pressure gauge. If the temperature increases slowly enough, the liquid and the vapor will be in *thermal equilibrium*. That is, the steam temperature will always be very nearly the same as that of the boiling water. So you will be measuring indirectly the change in boiling temperature with pressure.

These data will allow you to construct part of one of the lines of the P - T phase

diagram for water, the line separating the liquid and vapor regions. It will only be a small section of the diagram, but your experimental technique could be easily extended to cover the entire liquid-vapor line.

Exploring the Water Vapor in the Air

The amount of water vapor in the air, and its behavior with respect to changes in temperature and pressure, are of considerable importance in weather prediction. Fog, relative humidity, and dew point can be explained by understanding the phase diagram of water.

After another experiment with the pressure cooker, some simple methods will be described for measuring relative humidity and dew point using your thermistor. Later you will see how these quantities are related to the phase diagram, and how the phase diagram can be used to predict the probability of fog and dew formation.

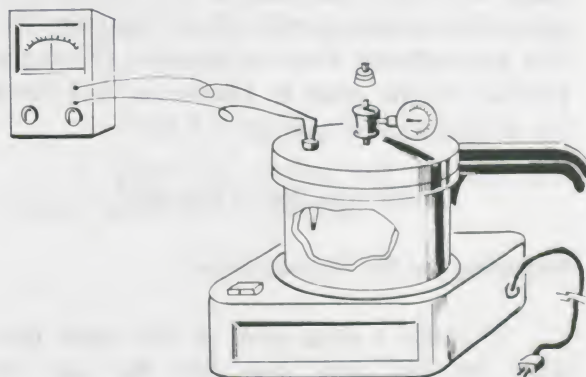
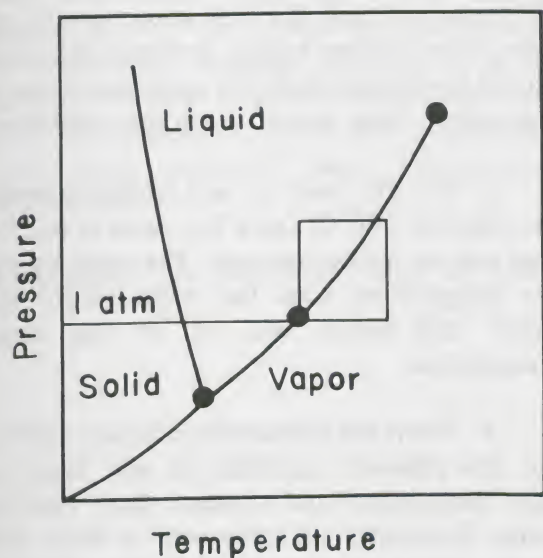


Figure 40.

EXPERIMENT C-1. Tracing Out Part of the Phase Diagram for Water

Calculating the Regulating Pressure

Before you begin the experiment you will use what you learned in Section B to calculate the pressure at which the regulating weight should release and begin to regulate the pressure. Since cooking time depends critically on temperature, the weight is necessary to keep the boiling temperature constant. This simple method works accurately and reliably.

1. *Measure the mass of the pressure-regulating weight* and record it in the space provided on the data page.

2. *Measure and record the diameter of the hole* on which the regulating weight fits. A simple way to do this is to insert rods (drills for example) of varying diameter until one exactly fits, and then measure its diameter with a vernier caliper or micrometer.

3. *Calculate the pressure* in the cooker which will produce an upward force on the weight just equal to the downward gravitational force on it. This is the pressure at which the weight should lift off and regulate. The gravitational force in newtons (N) is the product of the mass in kilograms (kg) times the acceleration of gravity, 9.8 m/s^2 .

$$F (\text{N}) = m (\text{kg}) \times 9.8 \text{ m/s}^2$$

Preparing for the Measurement

1. *Make a data table* in the space provided on the data page like the one for Section B, with columns for resistance, pressure and temperature. It is convenient to take data at one psi intervals, starting at zero (gauge).

2. *Attach the thermistor* to the cover

and check to see that it is operating properly. (Since the pressure inside will be greater than 1 atm be sure the stopper for the electrical feed through has its large end inside.) Zero the ohmmeter and check room temperature and perhaps one other point against your calibration scale. Readjust your calibration scale if necessary. An additional scale is provided on the data page.

3. *Record the atmospheric pressure* in your laboratory.

4. *Fill the pressure cooker with water* to a depth of about 1 to 2 cm.

Making the Measurement

The basic set-up for this measurement is illustrated in Figure 41. Following is a suggested procedure for taking your data. Review the procedure completely before beginning.

1. Bring the water quickly to a boil with the cover off and the hot plate turned on high. Once boiling begins, however, the heat should be reduced until the water *just* boils. It may take a little time to reach this condition.

2. Put the cover on and let the thermistor come to 100°C . Once the cover is on, the heat can be further reduced. The more slowly the temperature rises the more nearly the vapor and liquid will be at the same temperature.

3. When the thermistor indicates 100°C , put the pressure regulator on and begin to take temperature and pressure data. Tap the gauge frequently to make sure it reads correctly. Don't be concerned if the regulator hisses continuously; the seal is sufficiently good for your experiment.

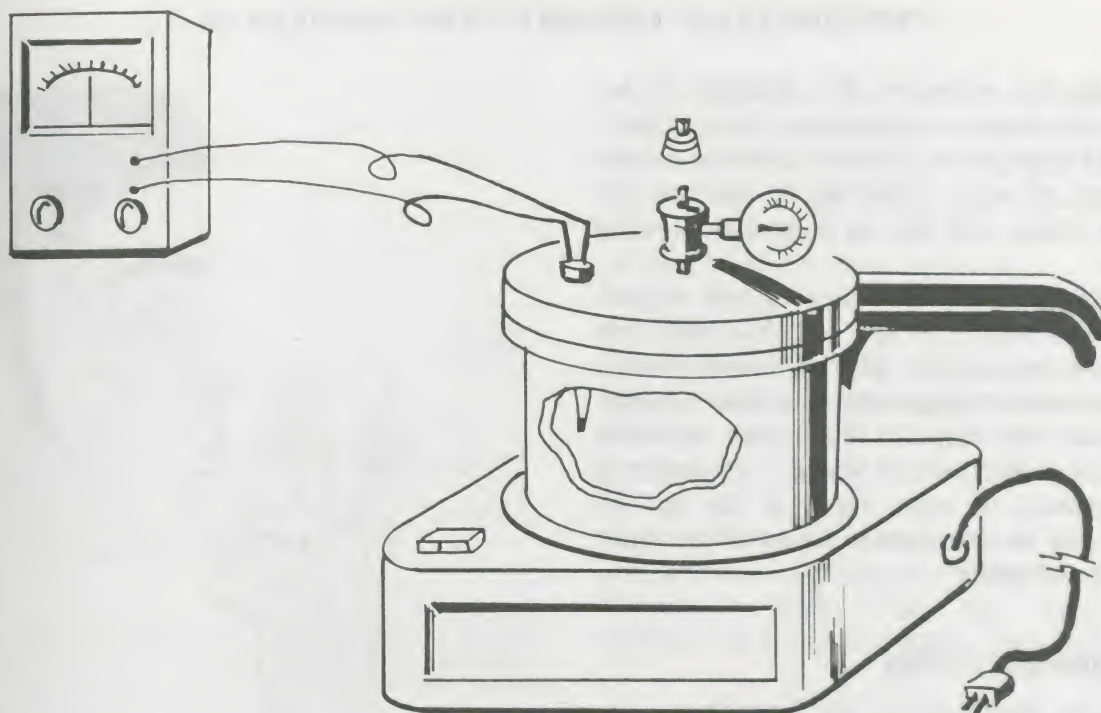


Figure 41.

4. When the regulating pressure is reached, the regulator should start rocking back and forth, supported by the escaping steam. Record the pressure and temperature at which this happens. How close is this pressure to your calculated value? How well does the regulator control the temperature? Can you observe any temperature fluctuation?

CAUTION: *Let the cooker cool or hold it*

under running cold water until the pressure is zero before removing the regulator. As the thermistor shows, the steam gets quite hot. Since it would release all its latent heat of vaporization if it condensed on your hands, the cooling procedure is important. (In other words, this BURNS.)

5. Take the cooker off the hot plate when P and T stop changing.

EXPERIMENT C-2. Exploring the Water Vapor in the Air

As the water in the pressure cooker boils, the steam disappears into the air. But it doesn't cease to be. There is always a certain amount of water vapor in the air and the steam mixes with the air as additional water vapor.

In these experiments you will explore the water vapor in the air. You will first examine *evaporation*, which is simply another mechanism for a liquid-to-vapor phase change. You will also measure the *relative humidity* and *dew point*, each of which is a measure of the amount of water vapor in the air. All these will be discussed in terms of the phase diagram of water.

Evaporational Cooling

A wet thermometer indicates a different temperature from a dry one, due to the evaporational cooling of the wetting substance. To feel this effect do the following:

1. Dip one finger in water and blow on that finger and the one next to it at the same time. Does the wet one feel cooler? Try dipping one finger in alcohol and compare this to a dry finger and to one dipped in water. (Figure 42.)

This difference in feeling can be made more precise by using a more accurate thermometer than your finger, for example your thermistor.

2. Measure the room temperature using your thermistor. Record this temperature in the data page as T_d (T_d).

3. Wrap the thermistor in a small water-soaked piece of paper towel or cotton. Be sure the water you use is at room temperature.

4. Wave the wrapped thermistor in the air briskly until its temperature stops chang-



Figure 42. Evaporational cooling can be demonstrated by blowing on two fingers one of which is wet. The wet finger feels colder.

ing. (Figure 43.) Record this as T_w (T_w). Note that the evaporating water has cooled the thermistor considerably, and by a specific amount.

5. Calculate the difference $\Delta T = T_d - T_w$ and record it.

Relative Humidity

To find the relative humidity from your evaporational cooling temperature, refer to the chart on page 76. Note that the temperatures on the chart are in $^{\circ}\text{F}$. Go down the column marked "Dry Bulb Reading" until you reach T_d , then go across the row until you reach the value under the "Dry-Wet Difference" equal to ΔT . This number is the relative humidity for the time and place of your measurements.

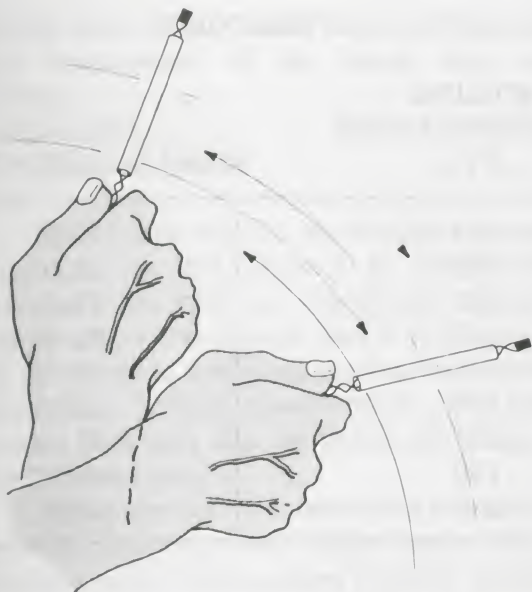


Figure 43. This feeling can be measured by waving a wet thermistor in the air. The equilibrium temperature of the wet thermistor is related to the relative humidity.

1. Determine the relative humidity, using the chart and your value of the dry-wet temperature difference. Be sure to convert your temperatures from $^{\circ}\text{C}$ to $^{\circ}\text{F}$ before using the table.

As you will see in more detail later in the module, the relative humidity is a measure of how much water vapor the air contains. The amount of water vapor already in the air seems to have an effect on the amount of evaporational cooling: the more water in the air, the less cooling occurs.

2. Wet the thermistor with rubbing alcohol and find a wet temperature as before. This will show that T_w depends on the wetting substance. Also try some oil. Since alcohol and oil are practically absent from the air, the effect of the air on each of them is about the same. Thus it follows that T_w depends on the properties of the wetting substance, as well as on how much of the substance is in the air.

Dew Point

If the air in the room were cooled to a low enough temperature, the water vapor in the air would condense, producing a fog. The temperature at which this occurs is called the *dew point*, and it depends only on the amount of water vapor in the air.

A simple way to measure this temperature is to cool a metal cup with ice water while measuring the cup's temperature. When the dew point is reached, the water vapor in the air will condense onto the cup. To perform the experiment, do the following.

1. Put warm water and ice in a metal cup and stir the mixture constantly with the thermistor. This keeps the temperature throughout the cup uniform. See Figure 44.

2. Record the temperature at which water droplets form on the cup. This temperature is called the *dew point temperature*.

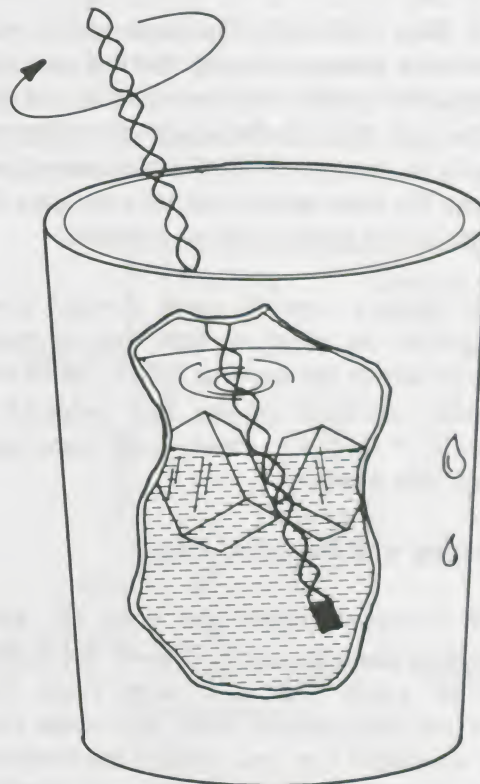


Figure 44.

ANALYSIS OF THE EXPERIMENT

You will begin your data analysis by plotting a graph of boiling temperature, as measured with your thermistor, against the pressure in the cooker. The resulting curve will indicate, over a limited range of values, how the temperature at which water boils depends on its total pressure. The procedure below will serve as a guide in preparing your graph.

Graphing Your Data

1. *Complete the data table.* As in the last experiment you must first convert your thermistor resistance values to temperatures, using your calibration scale. Also your gauge pressure readings must be converted into absolute values by adding the value of atmospheric pressure for the day. Since your pressure data was taken in psi it is probably most convenient to use these units.

2. *Plot the data.* For your graph you should plot pressure on the vertical axis and temperature on the horizontal axis. Let the pressure axis start at 0 psi and the temperature axis at around 80°C. Choose convenient divisions for your scales, but let your data fill as much of the graph paper as possible.

3. *Draw a smooth curve through your data points.* As usual be sure that as many points lie above the curve as below. Since you are quite confident of the first point ($P = 1 \text{ atm}$, $T = 100^\circ\text{C}$), make your curve pass through that point.

Comparing with Published Data

4. *Compare your data with the published data* given in Table VIII on the boiling point of water. Plot and label these data points on your graph. How well does your curve compare? Can you explain the irregularities in your data in terms of the experiment?

Table VIII.*

BOILING TEMPERATURE (°C)	PRESSURE (psi)
95	12.24
100	14.70
105	17.52
110	20.78
115	24.52
120	28.80
125	33.66
130	39.18
135	45.39

Now you have experimentally determined the change in boiling temperature with pressure for water. The remainder of the module is devoted to relating these results to the complete phase diagram for water, and to describing how other parts of the phase diagram can explain phenomena such as dew, fog and humidity.

UNDERSTANDING BOILING

Vapor Bubble Formation

Boiling is one process of vaporization. (Another is evaporation, which will be discussed later.) Vaporization is the process of changing from a liquid into a vapor. In boiling this process is a violent one. Vapor bubbles form deep in the liquid (wherever the heat is applied) and float to the surface where the vapor is released along with the latent heat that produced it. As you saw in Experiment A-2, when boiling begins, all of the input

*Table VIII gives published data on the variation of boiling temperature of water with pressure. For data over a wider range of temperature and for intermediate values see *The Handbook of Chemistry and Physics* under "Vapor Pressure of Water."

energy goes into creating vapor bubbles and the temperature of the liquid does not change.

The Effect of Pressure

In Experiment C-1 the boiling temperature rose as the pressure in the cooker increased. Bubbles are continually forming where the heat is applied. But if the pressure in the liquid is too great, the bubbles cannot form and boiling cannot occur. The heat energy then goes into the liquid and causes a temperature rise.

When the boiling temperature is reached, bubbles can form and boiling begins. Thus whether or not bubbles form depends on both temperature and pressure.

When boiling has started, if the pressure on the liquid is increased, bubbles are prevented from forming, and boiling stops. The heat again raises the liquid's temperature until it reaches a point where the bubbles can again form. Boiling then starts at this new, higher temperature and pressure.

What Happens in the Pressure Cooker

In the pressure cooker the increase in pressure is produced by the vapor itself. The pressure cooker is sealed so that the vapor created cannot escape. A situation is created in which the boiling temperature increases to keep pace with the increasing pressure. Therefore your data represent the conditions of temperature and pressure necessary for boiling to occur. (Figure 45.)

THE PHASE DIAGRAM OF WATER

As has been mentioned, it is not possible to describe the behavior of a substance which is undergoing a phase change by means of a single equation. Instead, the behavior of a substance is shown graphically in a *phase diagram*. Different types of phase diagrams

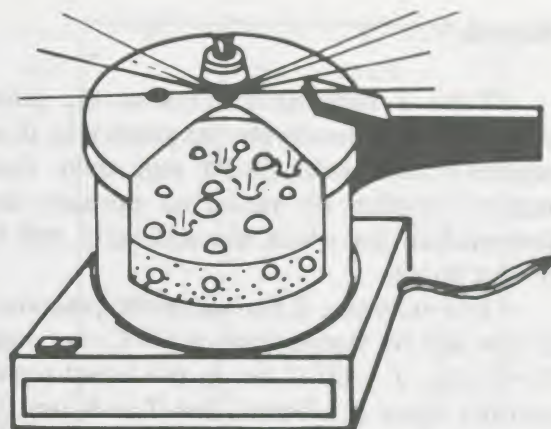


Figure 45.

display different properties of the substance. We will be concerned here with only the simplest of these, the P - T diagram.

The P - T diagram of water is shown in Figure 46. Note that the diagram is not to scale. It shows the general phase diagram shape but the pressure and temperature scales are not *linear*. This is done so that all of the interesting points of the graph can be displayed at once. Generally only a small section of the graph will be of interest at a given time. Several of these small sections are discussed in the following pages where they are displayed on a convenient scale.

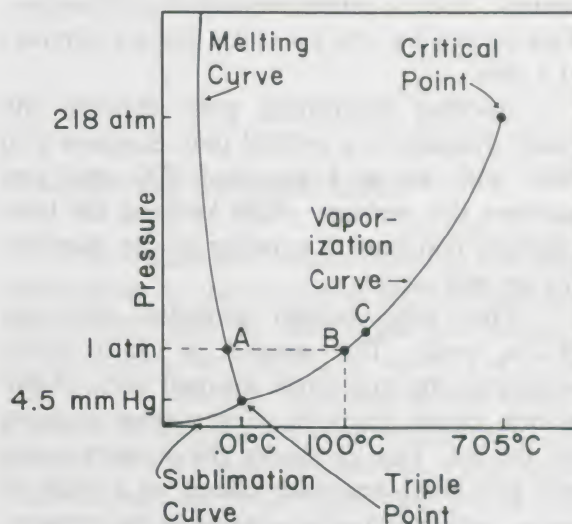


Figure 46. Schematic phase diagram of water.

Regions

Take a moment to look at the phase diagram. The lines divide the graph into three regions marked *solid*, *liquid*, and *vapor*. Each region includes all values of pressure and temperature for which the substance will be in that phase.

For example, if for water the pressure is 3 atm and its temperature is 60°C , the point $P = 3 \text{ atm}$, $T = 60^{\circ}\text{C}$ lies in the liquid region and the water is a liquid. But if at 3 atm the temperature were -20°C it would be a solid, (ice), and so on.

Phase Changes

Now what about phase changes? In Experiment A-2, you started with ice at atmospheric pressure and 0°C , which is point A in the diagram. You slowly increased the temperature while maintaining the pressure at one atmosphere. Your experiment followed the horizontal line across the melting curve, through all of the liquid region, and to the vaporization curve at point B, 100°C .

If you had performed the same experiment at a pressure of 1 mm Hg, you would have completely missed the liquid phase and gone directly from solid to vapor (ice to steam). Such a process is called *sublimation*. This occurs for dry ice (solid carbon dioxide) at 1 atm.

Another interesting path through the phase diagram is a vertical one. Suppose you start with ice at 1 atm and 0°C , and you increase the pressure while keeping the temperature constant. According to the diagram, the ice will melt.

This phenomenon explains why ice skates work. The weight of your body, supported by the small contact area of the blades, causes them to exert a large pressure on the ice. The ice under the runners melts and you skate smoothly along on a path of water, which refreezes as soon as the pressure is released.

Your Experiment

In Experiment C-1, you started at the boiling point of water (point B) and followed the vaporization curve. The boiling pressure and temperature steadily increased to some higher boiling point (point C).

A blow-up of this region to a large scale is shown in Figure 47. It is a graph of the published data given in Table VIII, and gives the boiling temperature of water for a range of pressures appropriate to cooking and sterilization.

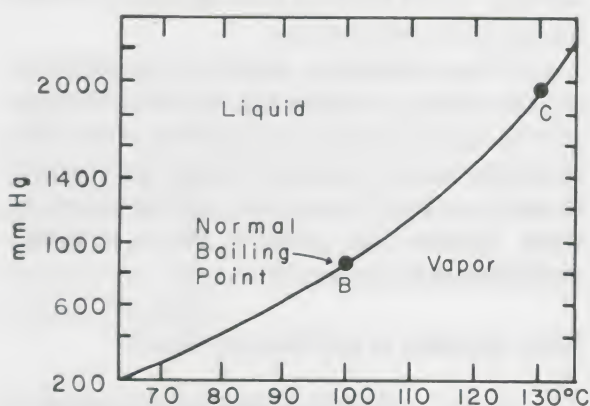


Figure 47.

Since atmospheric pressure varies with altitude, the lower portion of the curve is particularly important for localities at high altitude. With the lower boiling temperature which results from the lower pressure, cooking times must be increased.

This is true for cooking with the pressure cooker at high altitudes also, since the weight regulates at 15 psi above atmospheric pressure. For this reason pressure cooker manufacturers recommend that cooking time be increased 5% for every 1000 ft above the first 2000 ft. That is, 5% increase at 3000 ft, 10% at 4000 ft, and so on.

The Critical Point

The *critical point* is a point beyond which no distinction can be made between the liquid and the vapor phases. For water this occurs at an extremely high pressure (218 atm) and temperature (374°C). If you heat water under pressure in a strong container, when the critical point is reached, the usual line that separates the liquid below from the vapor above suddenly disappears. There are then no separate liquid and vapor phases. (Figure 48.)

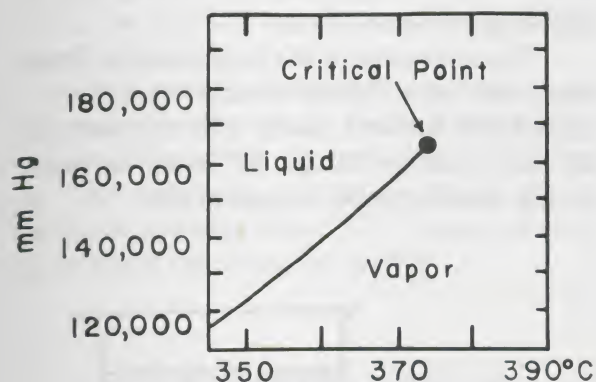


Figure 48.

The Triple Point

The triple point of water is the unique pressure and temperature (4.58 mm Hg and $.01^{\circ}\text{C}$) at which all three phase boundaries come together. Under these conditions all three phases are in equilibrium together. That is, the water will be boiling with ice floating in it and steam existing above it.

Since the triple point occurs at a unique temperature, this temperature is often used for calibrating thermometers.

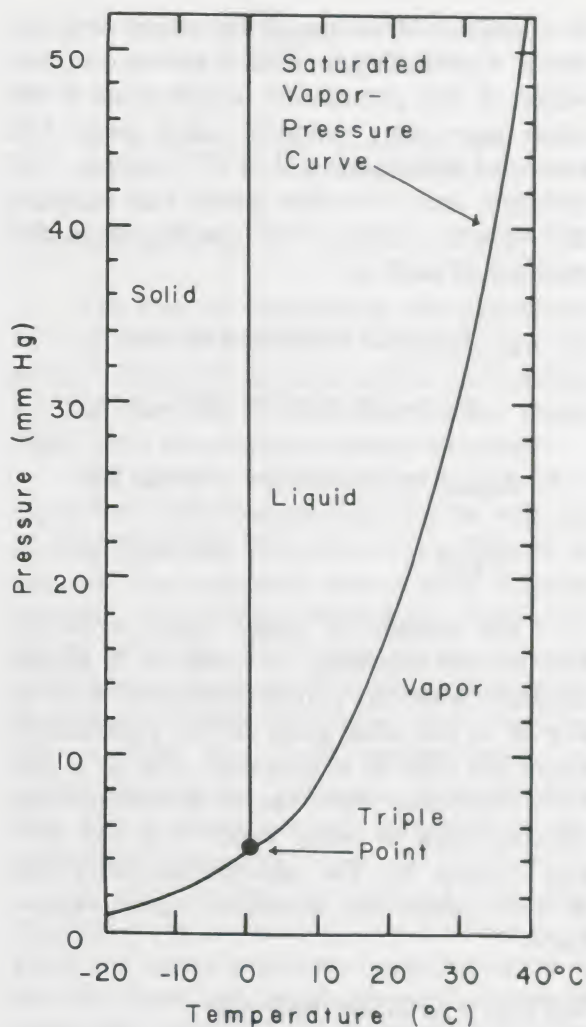


Figure 49.

Saturated Vapor-Pressure Curve

The behavior of water vapor in the air is determined by the section of the vaporization curve that lies in the range of outdoor temperatures, say -20°C to 40°C (-4°F to 104°F). In addition to showing the dependence of boiling temperature on pressure, this portion of the curve also indicates the maximum amount of water vapor that the air can hold at each temperature.

When gases are mixed together each acts,

to some extent, as though the others were not there. Thus each gas exerts a *partial pressure*, which is the pressure it would exert if the other gases were suddenly taken away. For example, air is composed of 21% oxygen, 78% nitrogen and 1% other gases. For standard atmospheric pressure, 760 mm Hg, the partial pressure of each is:

$$P_{\text{O}} = .21 \times 760 \approx 160 \text{ mm Hg}$$

$$P_{\text{N}} = .78 \times 760 \approx 593 \text{ mm Hg}$$

$$P_{\text{other}} = .01 \times 760 \approx \underline{8 \text{ mm Hg}}$$

$$P_{\text{atm}} = \quad \quad \quad 760 \text{ mm Hg}$$

The amount of water vapor in the air also can be expressed in terms of its partial pressure. When the partial pressure of water in the air is the value given on the vaporization curve for that air temperature, the air is said to be *saturated*. When the air is saturated the concentration of water vapor is as high as it can possibly be. The vaporization curve thus is also called the *saturated vapor-pressure curve*.

WATER VAPOR IN THE AIR

In the following pages we will explore the saturated vapor pressure as it relates to the water vapor in the air. This will help to explain evaporation, relative humidity and dew point.

EVAPORATION

Boiling is not the only type of vaporization. When wet clothes are left on a line, they dry; after a rain, the puddles disappear; when you blew on your wet fingers, they quickly dried. In each case the liquid converts to a vapor without boiling.

The process by which liquids vaporize without boiling is called *evaporation*. It

occurs at the surface of liquids rather than deep inside, as in boiling. To understand the evaporation process it is helpful to look at how and why an individual water molecule leaves the surface of the liquid.

A Microscopic View

If one could take an instantaneous, magnified picture of the region near the surface of the water, it would appear something like that shown in the figure. The molecules of the air (oxygen, nitrogen, water vapor, etc.) are quite far apart compared to their size. They are moving about at high speeds like a bunch of tiny BB's in a can, bouncing off each other and the walls many times a second with very little tendency to stick or get slowed down.

The molecules of the liquid, on the other hand, are quite tightly packed, with only a small space between them. This accounts for the fact that a volume of liquid is much heavier than the same volume of gas.

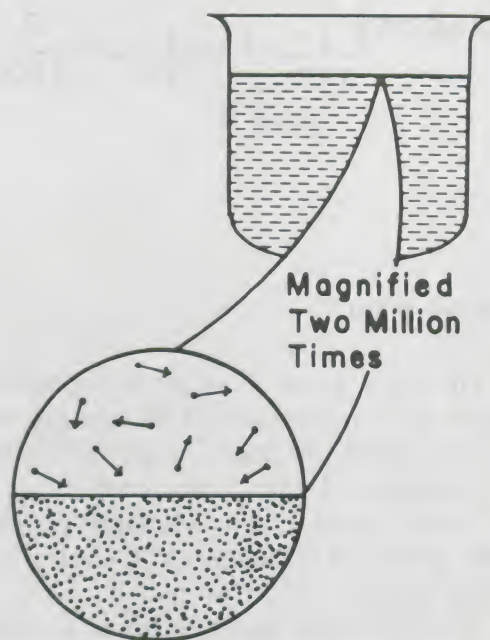


Figure 50.

The molecules in the liquid are also moving about at great speed. But since they are so close together they don't get very far between collisions. They slip through small gaps and jostle each other like shoppers in a crowded store.

When the molecules are as close together as they are in a liquid, there is a weak force of attraction between them. Surprising as it may seem, the reason that this force is able to hold molecules together to form the liquid phase is not well understood.

If a molecule near the surface gets going fast enough, by getting a hard bump for example, it can break free from the forces holding it in the liquid and, as we say, evaporate into the air. This is something like a rocket getting up enough speed to break free from the gravitational force of the earth and go off into space.

The energy necessary for a molecule to escape is directly related to the latent heat of vaporization which you measured in Section A. The following calculation shows that a molecule requires about 10^{-19} joules of energy to break free from the surface.

$$E = \frac{\text{ENERGY required to}}{\text{evaporate a MOLECULE}}$$

$$\text{Latent Heat} = \frac{\text{evaporation ENERGY}}{\text{per GRAM of water}}$$

$$L = \frac{2250 \text{ joules}}{\text{gram}}$$

The number (N) of molecules in one gram of water is calculated to be

$$N = \frac{3 \times 10^{22} \text{ molecules}}{\text{gram}}$$

$$E = \frac{L}{N} \left(\frac{\text{joules/gram}}{\text{molecule/gram}} \right)$$

$$= \frac{2250}{3 \times 10^{22}} \left(\frac{\text{joule}}{\text{molecule}} \right)$$

$$E = 7.5 \times 10^{-20} \left(\frac{\text{joule}}{\text{molecule}} \right)$$

Evaporation Rate

The rate of evaporation will depend on the number of molecules which escape per second. This rate, in turn, will be determined by the fraction of molecules in the liquid which have the energy necessary to escape.

The details of molecular energy in a liquid are quite complicated and we will not go into that here. However, it is sufficient to say that the molecules have a wide range of energies, with some having more and some having less. Also, the average energy increases with the temperature. This means that as the temperature of the liquid goes up, the number of molecules that have enough energy to escape also goes up. This accounts for the fact that the *evaporation rate increases as the temperature increases*.

It should also be pointed out that evaporation is a two-way street. That is, if there are water molecules bouncing about in the air above the liquid, some of these will strike the surface and stick there. Therefore, the rate of evaporation that you observe, will be the number of molecules escaping per second minus the number going back in per second. Thus the evaporation rate depends on the temperature of the liquid *and* on the amount of water vapor in the air above it.

The rate of evaporation is related to the saturated vapor-pressure curve.

Evaporation and the Saturated Vapor-Pressure Curve

The saturated vapor-pressure curve shows the pressure at which water will boil at each temperature. Another interpretation of this curve is that it represents the *equilibrium*

conditions for the liquid and vapor phases. For water sitting in air, this means that the temperature and the *partial pressure* of the water vapor in the air are just right for equilibrium to occur.

That is, liquid at any temperature tends toward having the vapor pressure above it equal to the value given on the vapor pressure curve for that temperature. If the *total* pressure on it is less than the curve value it will boil, giving off vapor until the equilibrium pressure is achieved or the liquid is gone. If the total pressure on it is greater than the curve value, as it often is in the air, then the liquid will evaporate until the partial pressure of the vapor comes up to the equilibrium value.

The *rate* of evaporation is proportional to how much the vapor pressure has to increase to come into equilibrium. That is, it is proportional to the difference between the *actual* partial pressure and the *saturated* partial pressure.

Evaporational Cooling

Our general picture also explains your observations of evaporational cooling. You observed that when water evaporates, the place it evaporates from is left colder. The reason is that only the hotter molecules evaporate (those with high energy), leaving the colder or lower energetic molecules behind. More high energy molecules are created through collisions to continue the evaporation, but the net result is a loss of energy and a corresponding decrease in temperature.

This happened when you waved the wet thermistor in the air. The water tried to achieve equilibrium with the vapor pressure of water in the air, but did it by getting colder. Since the thermistor was small, the evaporational cooling was able to drop its temperature to the equilibrium value given on the vapor-pressure curve for the partial pressure of water that was in the air. Thus, through the phase diagram, the equilibrium temperature may be used as a measure of the amount of water vapor in the air.

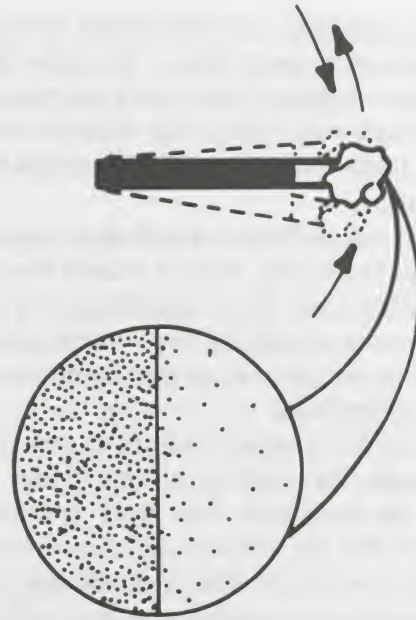


Figure 51. The water evaporating from the wet thermistor cooled it. The temperature dropped to the value on the vapor pressure curve for the amount of water vapor in the air.

RELATIVE HUMIDITY

Relative humidity is a measure of the amount of water vapor in the air. Usually it is defined as the percent ratio:

$$RH = \frac{M}{M_{\max}} \times 100\%$$

Here M is the amount of moisture (vapor) which is in the air and M_{\max} is the maximum amount of vapor (*saturation*) which the air could hold at that temperature. Thus relative humidity represents the percent of saturation of the air.

Relative humidity is important because it is directly related to the *evaporation rate*. If the air is unsaturated (a low relative humidity) then there will be a high evaporation rate and things will dry out quickly. If the air is highly saturated (a relative humidity near 100%) the evaporation rate is low and things take a long time to dry.

An Example

Figure 52 shows the portion of the phase diagram for water that relates to relative humidity. The curve represents the temperatures and pressures for which the liquid and vapor are in equilibrium, that is, for which there is no evaporation or condensation.

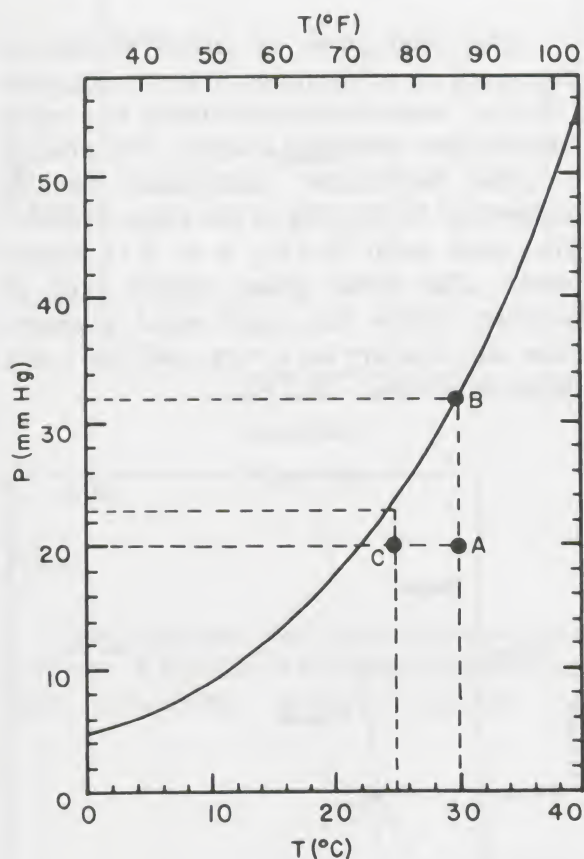


Figure 52.

In terms of the phase diagram the relative humidity is defined by the percent ratio:

$$RH = \frac{\text{actual partial pressure}}{\text{saturated partial pressure}} \times 100\%$$

For example, suppose the temperature is 30°C and the actual partial pressure of water in the air is 20 mm Hg (point A). The partial pressure required for saturation at that tem-

perature is 32 mm Hg (point B). Thus the relative humidity is:

$$RH = \frac{20 \text{ mm Hg}}{32 \text{ mm Hg}} \times 100\% = 63\%$$

If the temperature changes, so does the relative humidity, since the saturated vapor pressure depends on the temperature. For example, if the temperature drops to 25°C (point C) the relative humidity increases to:

$$RH = \frac{20 \text{ mm Hg}}{23 \text{ mm Hg}} \times 100\% = 87\%$$

This increase occurs even though the amount of water in the air has not changed.

DEW POINT

The *dew point* is the temperature at which the air is saturated for a given partial pressure of water vapor in the air. For temperatures above the dew point evaporation occurs. If the temperature falls below the dew point, condensation takes place.

In Experiment C-2 you measured the dew point temperature by cooling a cup in the air. When the temperature passes through the dew point, droplets of condensation formed on the side of the cup. The formation of such droplets on leaves, grass, and other outside surfaces as the temperature falls during the night is called "dew." Similar condensation on particles in the air is called "fog" or "clouds," depending on where it happens.

The dew point varies with the amount of water vapor in the air. The greater the amount of water vapor, the higher the dew point. A high dew point generally means a humid day, a low dew point a dry day. By referring to the phase diagram of water, one can determine the amount of water vapor (as specified by its partial pressure) if one knows the dew point.

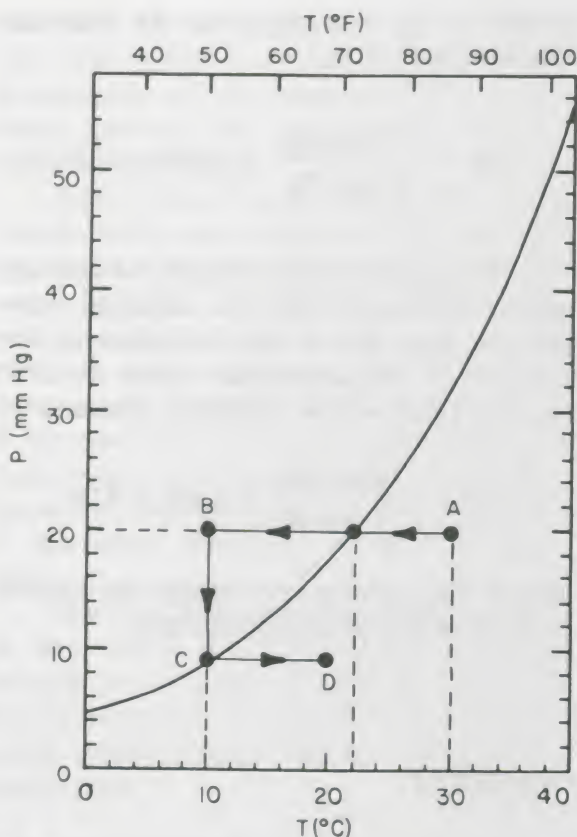


Figure 53.

An Example

Suppose the partial pressure of water in the air is 20 mm Hg. Then the dew point is 22°C. If the temperature outside is 30°C (point A in Figure 52) then water evaporates. However, if the temperature drops to 10°C (point B), then condensation begins. Condensation continues until the partial pressure of water vapor in the air drops to that determined by the vapor pressure curve at 10°C (point C).

If the air warms up again (point D), evaporation begins and will continue until the partial pressure builds up to that determined by the curve at this temperature.

The dew point is of practical importance for aviation and marine weather forecasting. For example, suppose the temperature at a certain airport is 72°F and the dew point is 70°F. If the temperature falls only 2°F, fog could form and result in dangerously low visibility.

PHASE DIAGRAMS OF OTHER SUBSTANCES

The behavior of many other materials can be explained by looking at their phase diagrams. Figure 54A, B, and C show three examples.

Carbon Dioxide

The solid phase of carbon dioxide is often used for refrigeration. It is referred to as "dry ice," since it converts directly to a vapor without first becoming a liquid. This process is called *sublimation*. Sublimation can be understood by looking at the phase diagram. The triple point of CO₂ is at 5.11 atmospheres. The liquid phase cannot exist at pressures below the triple point pressure. Note also that dry ice is very cold. At 1 atm its temperature is -78.2°C.

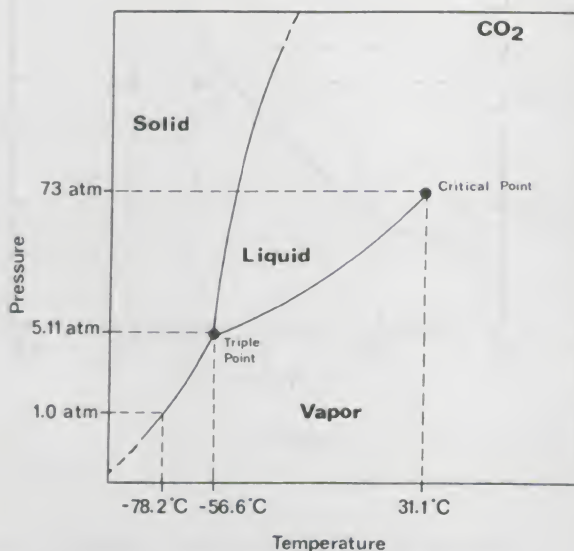


Figure 54A.

Propane

Propane is one of the common materials used for fuel. At atmospheric pressure and room temperature (21°C) it is a gas. When compressed above 8.5 atm (125 psi), however, it converts to a liquid. As a liquid it has a

much higher density, and can be transported in containers and by truck in much the same way as is gasoline. *But*, these containers must be able to withstand the high pressure.

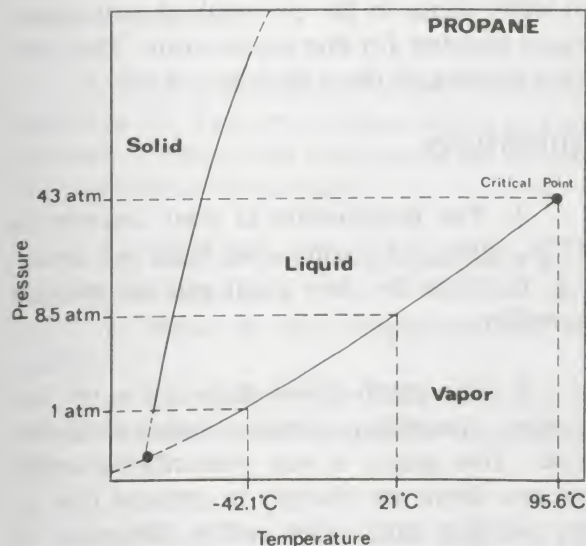


Figure 54B.

Freon

The substance used in most refrigerators is Freon. A portion of its phase diagram near room temperature is shown opposite. At

atmospheric pressure its liquid-vapor phase change occurs at -30°C (-22°F). Within the refrigerator, Freon is made to vaporize at a pressure of around 20 psi, thus absorbing energy in its latent heat. Later, in pipes outside the refrigerator, it recondenses at a pressure of about 100 psi, releasing the latent heat energy to the air.

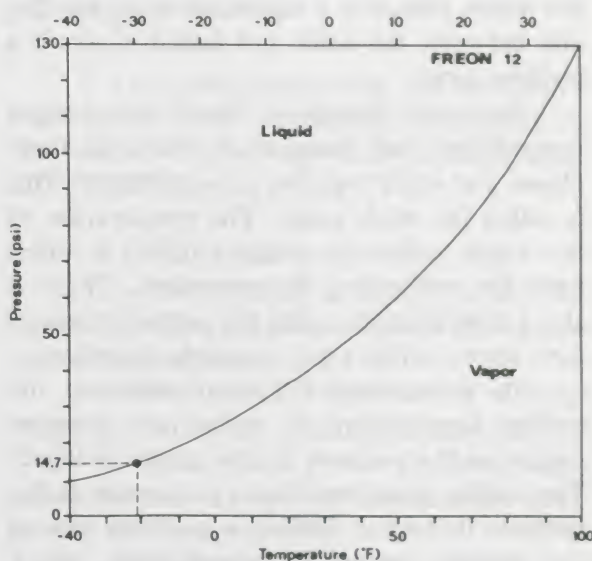


Figure 54C.

REVIEW: Summary of Section C

Section C of the module has been primarily concerned with changes between the liquid and vapor phases. These phase changes depend on the temperature and also on the pressure applied to the substance.

Phase changes are often represented by graphs of pressure against temperature, called *phase diagrams*. The lines on the graph represent boundaries between the solid, liquid, and gas phases. The line between the liquid and the vapor phases is a *vaporization curve*. The line between the solid and liquid phases is a *melting curve*.

For each substance there is a unique temperature and pressure at which all three phases can exist together in equilibrium. This is called the *triple point*. The temperature of the triple point for water ($.01^{\circ}\text{C}$) is often used for calibrating thermometers. There is also a temperature, called the *critical temperature*, above which a gas cannot be liquefied.

In Experiment C-1, you measured the boiling temperature of water in a pressure cooker as the pressure in the cooker changed. The boiling point was found to increase as the pressure increased. *Boiling* is a special case of the general process of *vaporization*, which refers to the change from liquid to vapor. Boiling occurs when vapor bubbles form in the liquid and rise to the surface without collapsing.

Evaporation is a slower process of vaporization that goes on at the surface of liquids. *Condensation* is the reverse of vaporization. It is the change from vapor to liquid.

In your data analysis, you drew a graph of boiling temperature against pressure. This was a small part of the phase diagram for water. Your graph is also a plot of the *saturated-vapor pressure* of water. When the vapor is in equilibrium with the liquid, then the space above the liquid is said to be *saturated*.

If several gases are mixed together then the pressure resulting from each one is called

its *partial pressure*. *Relative humidity* is the ratio of the *actual* partial pressure of water vapor to the *saturated* vapor pressure.

The *dew point* is the *temperature* at which the air becomes saturated with water vapor. At the dew point the partial pressure of water vapor in the air equals the saturated vapor pressure for that temperature. Then the air is holding all the water vapor it can.

QUESTIONS

1. The temperature at your location is 47°F , there is no wind, and there is a dense fog. Estimate the dew point and the relative humidity.

2. The graph below shows how, on the average, atmospheric pressure varies with altitude. This graph is not perfectly accurate because there are changes in pressure due to the weather and other causes. However, it does give a rough idea of the pressure variation. Notice that the pressure has fallen to about one-half the surface value at 18,000 feet.

The summit of Mt. Everest is at a height of about 29,000 feet. What is atmospheric pressure at that height?

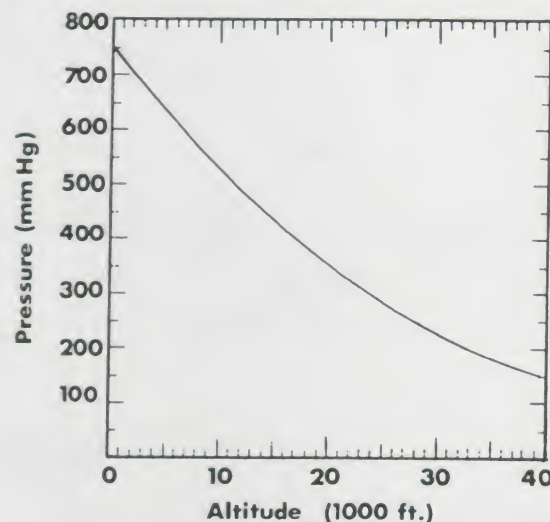


Figure 55.

Use the graph on page 74 to find the boiling point of water on top of Mt. Everest.

3. The city of Denver, Colorado is at a height of about 5,000 ft. Find the average atmospheric pressure and boiling point of water in Denver.

4. You have just moved to Denver (see question 3). You are cooking carrots in your pressure cooker. The regulator is set to hold the pressure at 15 psi gauge.

a. What is the maximum *absolute* pressure in the cooker?

b. What is the temperature in the cooker?

c. The cooker instruction book says to cook carrots for five minutes; is that enough time? Why?

5. During World War II, in England, fog was sometimes temporarily removed from a small area (such as an aircraft landing strip) by burning large quantities of gasoline or fuel oil. Explain briefly.

6. When water is boiling in a deep glass container you can see the bubbles increase in

size as they rise to the surface. Explain briefly.

7. Why do clothes dry slowly when the relative humidity is high?

8. In hot, dry places water is often kept in porous clay pots. These let some water get to the outside of the pot, so it is always wet. Why is water stored in this manner?

PROBLEMS

1. On a given humid day, the air temperature is 86°F (30°C). Moisture condenses on the outside of a tin cup when its temperature is 72°F (22°C).

a. What is the dew point?

b. Use the graph on page 71 to find the *saturated* vapor pressure of water at the dew point temperature.

c. What is the partial pressure of water vapor at the actual air temperature of 30°C?

d. What *would be* the saturated water vapor pressure at 30°C *if* the air were saturated at that temperature?

e. What is the relative humidity?

PSYCHROMETRIC TABLE FOR RELATIVE HUMIDITY

Table IX gives the relative humidity as determined from wet and dry bulb readings of temperature. It is called a psychrometric table after this technique for measuring the relative humidity. That is, a psychrometer is the

meterological term for a wet and dry bulb hygrometer, and a hygrometer is simply any instrument used for measuring the amount of moisture in the air.

Example: If dry bulb reading is 68° and wet bulb reading is 58° the relative humidity will be found in the 10° difference column opposite 68°. In this case 55%.

Table IX.

Dry-Wet Difference	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
30	89	78	68	57	47	37	27	17	8																					
32	90	79	69	60	50	41	31	22	13	4																				
34	90	81	72	62	53	44	35	27	18	9	1																			
36	91	82	73	65	56	48	39	31	23	14	6																			
38	91	83	75	67	59	51	43	35	27	19	12	4																		
40	92	84	76	68	61	53	46	38	31	23	16	9	2																	
42	92	85	77	70	62	55	48	41	34	28	21	14	7																	
44	93	85	78	71	64	57	51	44	37	31	24	18	12	5																
46	93	86	79	72	65	59	53	46	40	34	28	22	16	10	4															
48	93	87	80	73	67	60	54	48	42	36	31	25	19	14	8	3														
50	93	87	81	74	68	62	56	50	44	39	33	28	22	17	12	7	2													
52	94	88	81	75	69	63	58	52	46	41	36	30	25	20	15	10	6													
54	94	88	82	76	70	65	59	54	48	43	38	33	28	23	18	14	9	5												
56	94	88	82	77	71	66	61	55	50	45	40	35	31	26	21	17	12	8	4											
58	94	89	83	77	72	67	62	57	52	47	42	38	33	28	24	20	15	11	7	3										
60	94	89	84	78	73	68	63	58	53	49	44	39	35	31	27	22	18	14	10	6	2									
62	94	89	84	79	74	69	64	60	55	50	46	41	37	33	29	25	21	17	13	9	6	2								
64	95	90	85	79	75	70	66	61	56	52	48	43	39	35	31	27	23	20	16	12	9	5	2							
66	95	90	85	80	76	71	66	62	58	53	49	45	41	37	33	29	25	22	18	15	11	8	5	1						
68	95	90	85	81	76	72	67	63	59	55	51	47	43	39	35	31	28	24	21	17	14	11	8	4	1					
70	95	90	86	81	77	72	68	64	60	56	52	48	44	40	37	33	30	26	23	20	17	13	10	7	4	1				
72	95	91	86	82	78	73	69	65	61	57	53	49	46	42	39	35	32	28	25	22	19	16	13	10	7	4	1			
74	95	91	86	82	78	74	70	66	62	58	54	51	47	44	40	37	34	30	27	24	21	18	15	12	9	7	4	1		
76	96	91	87	83	78	74	70	67	63	59	55	52	48	45	42	38	35	32	29	26	23	20	17	14	12	9	6	4	1	
78	96	91	87	83	79	75	71	67	64	60	57	53	50	46	43	40	37	34	31	28	25	22	19	16	14	11	9	6	4	1
80	96	91	87	83	79	76	72	68	64	61	57	54	51	47	44	41	38	35	32	29	27	24	21	18	16	13	11	8	6	4
82	96	92	88	84	80	76	72	69	65	62	58	55	52	49	46	43	40	37	34	31	28	25	23	20	18	15	13	10	8	6
84	96	92	88	84	80	77	73	70	66	63	59	56	53	50	47	44	41	38	35	32	30	27	25	22	20	17	15	12	10	8
86	96	92	88	85	81	77	74	70	67	63	60	57	54	51	48	45	42	39	37	34	31	29	26	24	21	19	17	14	12	10
88	96	92	88	85	81	78	74	71	67	64	61	58	55	52	49	46	43	41	38	35	33	30	28	25	23	21	18	16	14	12
90	96	92	89	85	81	78	75	71	68	65	62	59	56	53	50	47	44	42	39	37	34	32	29	27	24	22	20	18	16	14
92	96	92	89	85	82	78	75	72	69	65	62	59	57	54	51	48	45	43	40	38	35	33	30	28	26	24	22	19	17	15
94	96	93	89	86	82	79	75	72	69	66	63	60	57	54	52	49	46	44	41	39	36	34	32	29	27	25	23	21	19	17
96	96	93	89	86	82	79	76	73	70	67	64	61	58	55	53	50	47	45	42	40	37	35	33	31	29	26	24	22	20	18
98	96	93	89	86	83	79	76	73	70	67	64	61	59	56	53	51	48	46	43	41	39	36	34	32	30	28	26	24	22	20
100	96	93	90	86	83	80	77	74	71	68	65	62	59	57	54	52	49	47	44	42	40	37	35	33	31	29	27	25	23	21
102	96	93	90	86	83	80	77	74	71	68	65	63	60	57	55	52	50	47	45	43	41	38	36	34	32	30	28	26	24	22
104	97	93	90	87	84	80	77	74	72	69	66	63	61	58	56	53	51	48	46	44	41	39	37	35	33	31	29	27	25	24
106	97	93	90	87	84	81	78	75	72	69	66	64	61	59	56	54	51	49	47	45	42	40	38	36	34	32	30	28	27	25
108	97	93	90	87	84	81	78	75	72	70	67	64	62	59	57	54	52	50	47	45	43	41	39	37	35	33	31	29	28	26

DATA PAGE

EXPERIMENT A-1. Learning to Use a Thermistor

Resistance of Thermistor: $\frac{\text{Scale Reading}}{\text{Multiplier}} \times \text{Range} = \text{Resistance}$

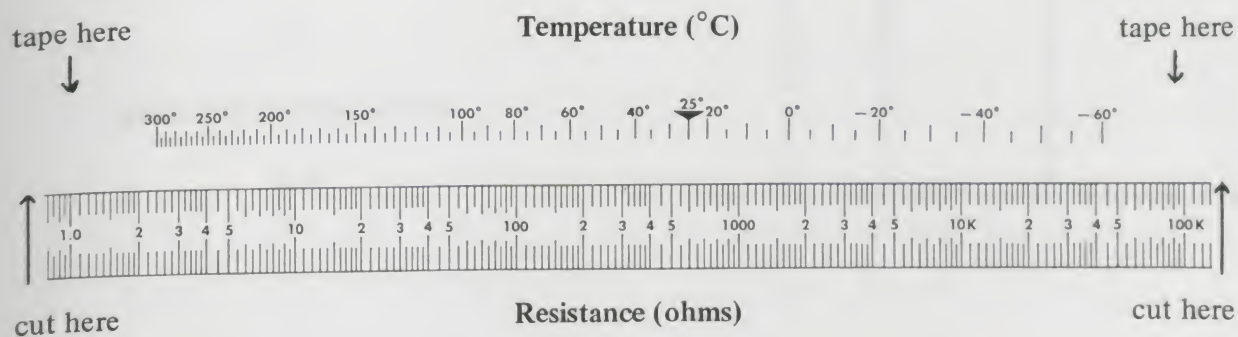
At Room Temperature: _____ \times _____ = _____

Room Temperature: _____ $^{\circ}\text{C}$

CHECKING THE CALIBRATION:

	Thermistor Resistance	Thermistor Temperature	Thermometer Temperature ($^{\circ}\text{C}$)
(mouth)			

Thermistor Curve Computer for use in Experiment A-2.



DATA PAGE

EXPERIMENT A-2. Measuring the Energies of Heating and Phase Changes

RESISTANCE OF IMMERSION
HEATER:

Temperature	Resistance

VOLTAGE NECESSARY TO DELIVER 160
WATTS:

$$V \text{ (volts)} = \sqrt{P \text{ (watts)} \times R \text{ (ohms)}}$$

$$= \sqrt{160 R}$$

DATA PAGE

Mass of H_2O
(initial conditions)

Thermos = _____ g

Thermos
plus
water = _____ g

Thermos
plus ice
plus water = _____ g

water = _____ g

ice = _____ g

(final conditions)

Thermos
plus = _____ g
water

water
left = _____ g

water
boiled
away = _____ g

Specific heat of water:

°C =

Latent heat of melting:

$$L =$$

Latent heat of vaporization:

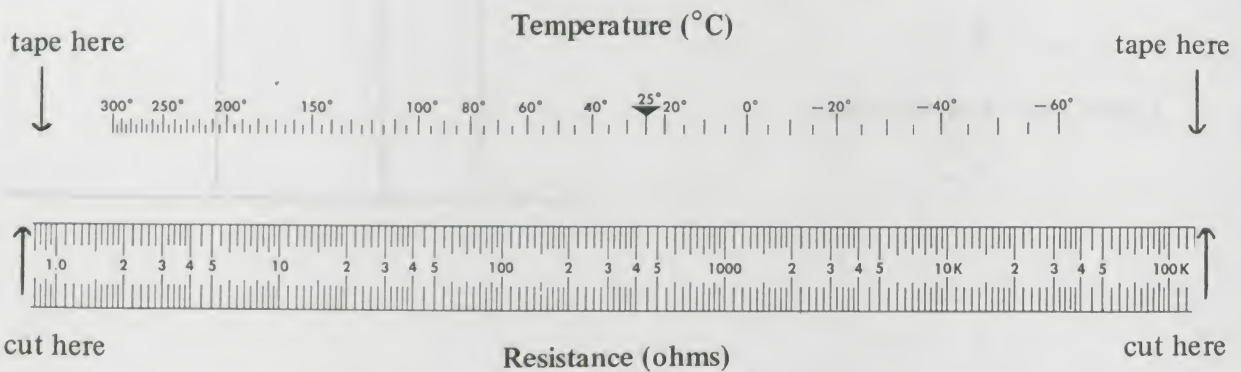
$$L =$$
[illegible]

DATA PAGE
(make table here)

EXPERIMENT B-1. Measuring Pressure Versus Temperature

Room Temperature:

Atmospheric Pressure:



DATA PAGE

EXPERIMENT C-1. Tracing Out Part of the Phase Diagram for Water

CALCULATION OF THE REGULATING PRESSURE:

Pressure Regulating Weight:

(Make Data Table Here)

$$m =$$

Pressure Cooker Hole:

$$d =$$

Calculated Lift-Off Pressure:

$$P = \frac{\text{Force}}{\text{Area}}$$

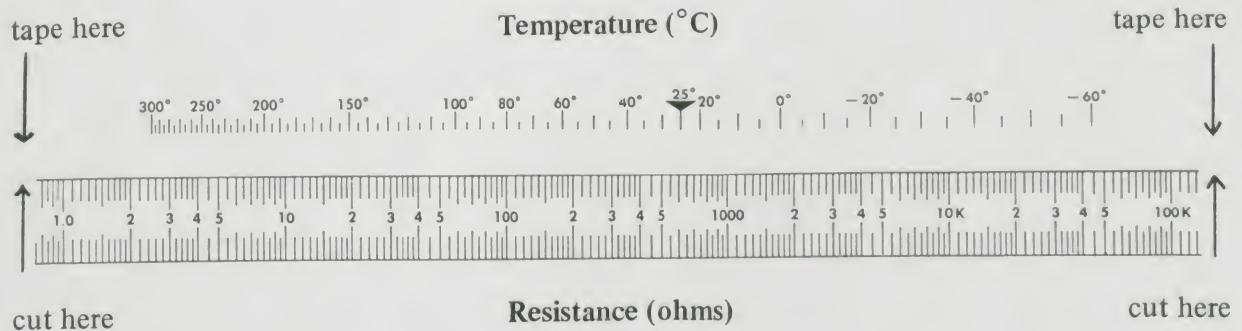
$$=$$

Observed Lift-Off Pressure:

$$P =$$

Temperature at this Pressure:

$$T =$$



DATA PAGE

EXPERIMENT C-2. Exploring the Water Vapor in the Air

EVAPORATIONAL COOLING:

Room Temperature Dry: $T_d =$

Room Temperature Wet: $T_w =$

Temperature Difference: $\Delta T = T_d - T_w$

=

RELATIVE HUMIDITY: $R. H. =$
(from chart, page 76)

DEW POINT: $T =$

07-001730-1

